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A Study of Vegetation Problems Associated with Refuse Landfills

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16. ABSTRACT

A mail survey of about 1,000 individuals, was conducted for the purpose of determining the status of landfill vegetation growth. Of the 500 people responding, about 75 percent reported no problems. Twenty-five percent reported problems on landfills and 7 percent reported problems with vegetation adjacent to landfills. Site visits were selected to represent the nine major climatic regions as defined by Trewartha. About 60 individual landfills were visited, and comparisons of the quality of soil atmospheres were made in the root zones of healthy specimens and individuals of the same species that were dead or dying. Comparisons of soil quality were made likewise. Where landfill gases were high in concentration, elevated concentrations of available ammonia-N, moisture and the trace elements iron, manganese, copper, and zinc were found--changes similar to those found in flooded soils. Also, high soil temperatures were found associated with landfill gases in a number of cases. Landfill vegetation growth conditions were generally similar for most of the climatic regions visited.

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TABLE J-10. (continued)

LIST OF ABBREVIATIONS*

Mg -- Magnesium

P -- Phosphorus

K -- Potassium

Ca -- Calcium

NH_3-N -- Ammonia-nitrogen

NO_3-N -- Nitrate-nitrogen

H_2O -- Moisture

O.M. -- Organic Matter

Fe -- Iron

Mn -- Manganese

Cu -- Copper

Zn -- Zinc

B -- Boron

Fe/Mn -- Iron/Manganese

C. -- Conductivity

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A STUDY OF VEGETATION PROBLEMS ASSOCIATED WITH REFUSE LANDFILLS

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FOREWORD

The Environmental Protection Agency (EPA) was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollution discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research, a most vital communication's link between the researcher and the user community.

The ultimate use of refuse landfills involves the planting of vegetation. The problems of growing deep-rooted vegetation over former landfills has been studied through literature surveys, a mail survey of the United States and its possessions, and by on-site evaluations of vegetation growth at former landfills within the major climatic zones of the continental United States and Puerto Rico. It was the purpose of these studies to determine the geographic extent of problems associated with vegetating completed landfills throughout the United States.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

ABSTRACT

A mail survey of about 1,000 individuals, presumed to be knowledgable of the vegetation associated with operating and completed landfills throughout the continental United States and territories, was conducted for the purpose of determining the status of landfill vegetation growth. Of the 500 people responding, about 75 percent reported no problems. Twenty-five percent reported problems on landfills and 7 percent reported problems with vegetation adjacent to landfills.

Using reports received through the mail survey, landfills for site visits were selected to represent the nine major climatic regions as defined by Trewartha. About 60 individual landfills were visited, and comparisons of the quality of soil atmospheres were made in the root zones of healthy specimens and individuals of the same species that were dead or dying. Almost invariably, where soil atmospheres contained high concentrations of landfill gases, vegetation was adversely affected.

Comparisons of soil quality were made likewise. In almost all cases where landfill gases were high in concentration, elevated concentrations of available ammonia-N, moisture and the trace elements iron, manganese, copper, and zinc were found--changes similar to those found in flooded soils. Also, high soil temperatures were found associated with landfill gases in a number of cases.

Landfill vegetation growth conditions were generally similar for most of the climatic regions visited. Those in the desert area, however, were found to have somewhat lower landfill gas concentrations than the others--possibly due to dry conditions.

This report was submitted in fulfillment of Contract No. R 803762-02 by Rutgers University under the sponsorship of the United States Environmental Protection Agency. This report covers the period May 15, 1975 to May 14, 1977, and the work was completed as of June 15, 1977.

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SECTION I

INTRODUCTION

Sanitary Landfill has been demonstrated to be the least expensive environmentally acceptable means of waste disposal available to date, purportedly possessing the attributes of neatness and safety in addition to the relatively low cost. Whereas such sites may have originally been located at considerable distances from residential areas, rapid urban and suburban development in the United States has caused many once remote dumping grounds to be within developed areas. As such they provide an attractive source of much needed land for many purposes. Although conversion to recreational areas or other nonstructural usage has long been considered an acceptable end for completed landfill sites, the urgent need for space and for increased tax revenues has caused many municipalities to eye completed landfills for commercial use as well. In rural areas, intensifying land use has resulted in attempts to use completed landfills for growing commercial crops.

Regardless of the ultimate utilization of the landfill, certain serious disadvantages are inherent, not the least of which are ecological upsets due to leaching of infiltrates and gases into groundwater, pollution of water supplies, the production of toxic and explosive gas mixtures from anaerobic microbial decomposition of the organic matter present, and surface settlement. High ground temperatures have also been reported in the cover material of some completed refuse landfills.

The state of New Jersey, with a population of approximately 7½ million, has experienced vegetation growth problems on and around refuse landfills. The state is currently serving as the repository for solid waste from a population of approximately 10 million. There are some 300 active landfill sites in New Jersey comprising approximately 10,000 acres that predictably will become filled in the next few years. There are also in existence within the state some 150 completed landfills, many of which have already been converted to some of the aforementioned uses. Landfills completed up to World War II were shallower and contained less organic matter than the present ones, possibly as the result of more coal ashes, more open burning, and less wastage during those earlier times. Since World War II the amount of disposable waste has risen considerably with a concomitant rise in content of biodegradable material. It is believed that the changing character of the waste in landfills and the increasing need to develop former landfills for new land have helped make vegetation deaths more noticeable. More than half a dozen landfill sites in New Jersey were known to have experienced this problem.

With the death of vegetation associated with landfills well documented in New Jersey, it was desirable to see if similar situations existed in other parts of the United States and to examine possible causes of these vegetation growth problems. The survey of the quality of landfill vegetation growth consisted of a mail survey of the United States followed by on-site visits to former landfills in all the major meterological regions found in the 48 continental states and Puerto Rico.

SECTION II

CONCLUSIONS

1. A mail survey of some 1,000 persons assumed to be knowledgeable of plant growth status on or adjacent to completed landfills showed fully 75 percent of those who responded as unaware of the problems associated with vegetating completed landfills.

2. Site visits to some 60 completed landfills within nine climatic regions of the United States generally revealed a high negative correlation between plant growth and concentrations of methane and/or carbon dioxide in the root atmospheres.

3. Little variability in the magnitude of landfill gas production and consequent vegetation damage was observed among the different climatic regions, except for the arid area (southwestern Arizona) where concentrations of combustible gas and carbon dioxide were found to be somewhat less than in the eight other regions. This was presumably due to the lack of rainfall.

4. A number of woody species including American linden, American elm, Japanese spreading yew, and sugar maple were found to be particularly sensitive to landfill conditions.

5. The degree of sensitivity to landfill conditions among the woody species closely paralleled relative tolerance of these species to flooded or water-logged soils.

6. Soil characteristics, other than atmospheric quality modified by the presence of anaerobically produced landfill gases, included content of moisture and available ammonia-nitrogen, iron, manganese, zinc, and copper--all of which increased significantly in landfill gassed soils. Increased availability of these elements is believed to be due to the highly reduced conditions in the soils and the activity of anaerobic microorganisms. Soil pH tended to approach neutrality in gassed soils due to the presence of organic acids produced during anaerobic decomposition of the buried refuse.

7. Where attempts were made to prevent the migration of landfill gases into plant root zones through the use of impermeable barriers, vertical venting or gas extraction systems, or through planting in mounds of earth placed atop landfills, plants appeared to have a better chance of survival.

8. Occasionally high soil temperatures (up to 60°C) adverse to vegetation growth were found associated with landfill gases in the soil.

SECTION III

RECOMMENDATIONS

1. The lack of awareness of landfill managers of the problems attendant on establishing vegetation on landfill sites indicates the need for education along these lines. It was also found that in about one third of the cases there were discrepancies between conditions reported in the mail survey and those found in on-site visits to the landfills.

2. The variability in landfill gas tolerance among species suggests the need for research aimed at screening plant species for their adaptability to landfill gases.

3. The similarities between soil characteristics in landfill cover soils and in water-logged soils suggests the use of flood resistant species for landfill plantings.

4. The lack of understanding of the precise role of specific landfill gases in causing plant deterioration suggests the need for research aimed at clarifying this situation.

5. To grow healthy vegetation, landfill gases should be prevented from entering the plant root atmospheres.

SECTION IV

LITERATURE SURVEY

GAS PRODUCTION IN REFUSE LANDFILLS

The composition of landfill refuse varies considerably depending on its origin be it municipal, industrial, incineration material or sewerage sludge. The organic content of solid waste collected from homes, schools, commercial establishments and industries generally ranges from 50 to 75% on a weight basis. Most of these organics are biodegradable and can be broken down into simpler compounds by both aerobic and anaerobic micro-organisms. The rate at which this occurs is reported to be a function of (a) permeability of cover material (b) depth of garbage (c) amount of rainfall (d) moisture content of the refuse (e) putrescibility of the refuse (f) compaction (g) pH and (h) age of the landfill (1, 2,).

When the refuse is initially deposited in the landfill, there is enough oxygen present to support a population of aerobic bacteria. This stage lasts from one day to many months (3). The literature indicates CO_2, NH_3, and H_2O to be the principle products formed in aerobic decomposition (4).

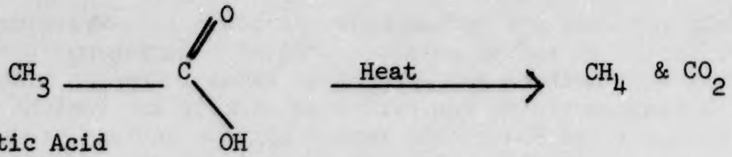
The depletion of soil oxygen results in a decrease in the aerobic and an increase in the anaerobic population. During the anaerobic stage of decomposition two phases have been identified, a non-methanogenic stage followed by a methane-producing stage.

During the non-methanogenic stage, organic matter is reduced, in the presence of water and extracellular enzymes produced from bacteria, to smaller soluble components which include fatty acids, simple sugars, amino acids and other light weight compounds (5). Further breakdown of soluble compounds in the absence of oxygen produces H_2, CO, NH_3, H_2O, CO_2 and organic acids (probably acetic acid) (5, 6, 7)

During the methanogenic stage, CO_2 and CH_4 are the principle gases produced. They originate from two reactions carried out by a bacterium called Methanobacterium(6). In the first reaction, the CO_2 produced earlier in the decomposition is reduced through the addition of hydrogen to form methane and water. The second reaction utilizes the acetic acid produced during the non-methanogenic stage. Acetic acid is cleaved in the presence of heat to form methane and carbon dioxide. These two reactions are represented below:

$$(1) \quad CO_2 \xrightarrow{\quad 4H_2 \quad} CH_4 \ \& \ 2\ H_2O \ \& \ \text{Heat}$$

(2)



Acetic Acid

Various other gases reportedly produced in the anaerobic environment of the landfill include ethane, propane, phosphine, hydrogen sulfide, nitrogen and nitrous oxide (8,9,10,11,5). A literature search of studies concerning the effects on vegetation in response to the presence of these six gases in the root zones produced a single article from Japan(12). Hydrogen sulfide, which is produced from the bacterium Desulfovibrio desulfuricans in alkaline conditions (13), was reported to have caused lower root respiration rates and a decrease in soil nematode population (14).

In addition to the methane-producing bacteria mentioned above, there exists a bacterium, Pseudomonas chromobacterium, which utilizes methane during its metabolism. It oxidizes methane, producing carbon dioxide and water (15). Since oxygen is required for this reaction, these bacteria will generally be found near the upper surface of the landfill.

During the oxidation of methane, oxygen in consumed. This raises a question of whether or not the oxygen concentration is a limiting factor in this reaction. Hoeks points out that these organisms can function at soil atmospheric oxygen concentrations as low as 1%. However, at this low concentration, incomplete oxidation causes formation of such intermediate side products as methanol, formaldehyde and formic acid (15).

During anaerobic decomposition, the possibility exists for production of a wide range of gases and liquids. However, the literature indicates CO_2, H_2, CH_4, H_2S, and N_2 to be the predominant gases with CO_2 and CH_4 making up the largest portion of the soil gas atmosphere. There has been a considerable amount of work done concerning the effects of excess CO_2 in the root zone on different plant species. In 1914, Noyes saturated soil around tomato and corn plants with CO_2(16). Both species died within two weeks, but there was no irreversible damage to the soil.

A good deal of variation in tolerence between species has been found. Cotton seedlings grown in hydroponic solutions (17) were able to exhibit optimum growth with 10% CO_2 present, provided at least 7.5% O_2 was also present. Thirty to 40 percent CO_2 in the root zone of cotton seedlings was found to severely reduce root growth in hydroponic solutions. Red and black raspberry (18) were killed when their roots were exposed to 10% CO_2.

Norris, Wiegand, and Johanson (19) in 1959 exposed excised onion root tips to CO_2 concentrations above that normally found in soil atmospheres. They concluded that an observed decrease in respiration rate was due to permanent damage to the root cells caused by the lowering of the intercellular pH by dissolved CO_2.

There are various factors influencing methane gas production. The parameters most commonly reported are refuse moisture content, temperature and pH. Probably the major factor is refuse moisture content. Ramaswamy (20) and Songonuga (21) found that methane gas production rates increased with refuse moisture content, a maximum production occurring at moisture content of 60 to 80% wet weight. Farquhar and Rovers (6) report maximum methane production when refuse is near the saturation point. An experiment carried out by Merz and Stone (22) concluded that methane gas production increased with the addition of surface irrigation water. Ludwig (23) found that at one of two sites in California methane production increased after a heavy rainfall.

It is reported that refuse moisture content too low to support continuous gas production in a landfill may be in the range of 30 to 40% (22). This condition may exist in certain areas of the United States such as the dry southwest, where rainfall and relative humidity are very low.

Temperature has also been described as a limiting factor in methane gas production. Aerobic conditions invariably produce higher temperatures than anaerobic (24,22). Three separate articles have reported optimum temperatures for methane production ranging from 30°C to 37°C. Kotze et al (7) report 37°C to be the optimum temperature for methane gas production in the mesophilic stage of sewage sludge decomposition. Dobson (25) and Ramaswamy (20) say maximum gas production occurs at 30°C and 35°C respectively. All found that deviations from the optimum temperature resulted in decreased methane production rates.

The optimum pH for methane production during anaerobic decomposition of sewage sludge is very near 7.0 (6). As deviations from this optimum are encountered, gas production is decreased. Extremely high pH may exist in the refuse because of the presence of alkaline materials, whereas low pH levels can result in inhibition of methane production with the concomitant formation of organic acids (6).

One parameter which was measured in a number of studies was the effect of excessive infiltration on methane production. When large amounts of water were added to a lysimeter filled with refuse so that the saturation point was almost reached, methane production was inhibited; however, CO_2 continued to be produced. This response was attributed to the positive oxidation-reduction potential of rain water suppressing the activity of methanogenic bacteria which require a negative oxidation-reduction potential (26).

HISTORY OF PROBLEMS IN VEGETATING LANDFILLS

Conversion to recreational areas or other non-structural usage has been considered an acceptable end for completed landfill sites and, in rural areas, intensifying land use has resulted in attempts to use completed landfills for growing commercial crops (27, 10, 28, 29, 30, 31, 32, 33).

The serious disadvantages for adequate vegetation growth inherent in landfill sites have been enumerated namely, the production of toxic gas mixtures from anaerobic decomposition of organic matter present, the leaching of infiltrates and gases into ground water supplies, and the high ground temperatures (34, 10, 35).

In spite of predictable negative success in utilizing landfills for the support of vegetation, many reports of success or proposals for transforming barren former refuse sites into luxuriant vegetated areas are appearing in the literature and in the press (36, 37, 38, 39, 32, 40).

In July, 1972 an article by Duane(41) applauding the construction of golf courses on completed sanitary landfills cited the successful use of such tree species as Japanese black pine, London plane, thornless honey locust and Russian olive for beautifying the sites. In 1973, an anonymous article entitled "From Refuse Heap to Botanic Garden" appeared in Solid Wastes Management magazine describing the transformation of an 87-acre landfill in Los Angeles that had the distinction of being one of the world's first such phenomena (42).

A catalogue published in 1973 describing hybrid poplars bred by a Pennsylvania nursery cites a particular hybrid which supposedly was grown successfully on a landfill site at Fort Dix, New Jersey (43). In that same year, a brochure was published by the Caterpillar Tractor Company describing and displaying in lavish color various successfully vegetated golf courses and parks in Mountain View, California; Anoka, Minnesota; Baltimore County, Maryland; Long Island, New York; Alton and Chicago, Illinois (44). In 1974 a news item in the Sun-Star of Merced, California described a 5-acre park whose new grass and trees would be aided in growth by "the proximity to the refuse which will provide needed nutrients" (45).

Few problems if any were either observed or anticipated in achieving these spectacular results with the exception of the report of root damage to large trees and shrubs at the Los Angeles Botanic Garden site.

At the same time, various investigators were experiencing difficulties in growing vegetation at similar sites. In January 1969, Professor F. Flower and associates of Rutgers University in New Brunswick, New Jersey (46), responding to a complaint of vegetation death on private properties adjacent to a landfill in Cherry Hill Township observed dead trees and shrubs of the following species: spruce, rhododendron, Japanese yew, azalea, dogwood, flowering peach, brush dogwood, Scotch broom, arborvitae, Douglas fir, and lawn grasses. Testing of the soil with appropriate equipment disclosed high concentrations of carbon dioxide and explosive gases. The conclusion reached was that the trees and shrubs could have been killed by displacement of oxygen from their root zones by lateral movement of the gases of refuse decomposition.

This site was visited periodically from 1969 to the present time, soil gas was tested for explosive gas content and vegetation around the homes evaluated for gas effects (47).

Subsequent visits were made to the site on March 12, March 18, and March 31, 1975 (48). Examination of the landfill area on which a park had been constructed revealed that many trees had been planted over the area the previous fall. The species included sweet gum, red oak, Japanese poplar, white pine, Scotch pine and fir among others. Some of the trees had been destroyed by being pulled out by their roots. The holes remaining were rather shallow indicating that plantings were not made at a great enough depth.

The needles on some evergreen were brown indicating little likelihood of survival.

Gas vents had been installed consisting of plastic pipes with holes placed vertically in the ground.

Leachate was found in some spots. Grass growth throughout the park was spotty; in some areas it grew well, whereas in other areas, very poorly.

A return visit to the site on May 28, 1975 (49) was made to evaluate the quality of the vegetation which had been planted over the area. Most of the trees were still living with the exception of a large number of Austrian pines and Scotch pines. The firs, white pines, and deciduous trees in most cases were doing very well.

Ground gas samples were taken and in most cases gas was not encountered until a depth of 15 to 25 inches was reached. In only one case was there evidence of high combustible gas level in the root zone of a deciduous tree and that tree had died. Vetch, clover, grasses and weeds covered much of the area; some spots were noted to be barren. Ground gas was found very close to the surface in some of the latter areas. Signs of leachate were also noted at a few locations.

Checks for combustible gas were made in several of the vertical venting pipes, results of which indicated that these pipes were venting the gases from the landfill. It was concluded that a hard layer at the base of the 2 to 3 feet of cover material had successfully sealed off the combustible gases from the root zone of trees, forcing the gas to move laterally to the venting pipes whence they were being dispersed to the atmosphere. The vents probably reduced underground lateral migration of gases away from the landfill, although a single check in this area showed combustible gas to be present.

In 1972, the Rutgers contingent made a visit to the peach orchard of the De Eugenio brothers in Glassboro, New Jersey which bordered on a completed landfill, where approximately 50 peach trees had died (47). Upon completion of the landfill, the growers had hoped to plant additional peach trees on the filled area. Examination of the soil atmosphere revealed high concentrations of carbon dioxide and explosive gases in the orchard area.

The conclusion was that carbon dioxide and methane from the anaerobic decomposition of organic matter had moved laterally from the landfill into the orchard area. The sealing of the surface of the landfill with a soil cover had probably been sufficient to prohibit the free passage of gases vertically out of the landfill, therefore, they had taken an easier route laterally into the soil in the root area of peach trees adjacent to the landfill.

A return visit was made to the De Eugenio orchard on March 18, 1975 (50). There had been further peach tree death from lateral migration of the landfill gases. No corrective measures had been taken.

In May, 1973 the Rutgers group visited the Hunter Farm in Cinnaminson, New Jersey where previous visits had confirmed that combustible gases from an adjacent landfill had encroached upon the farmland and injured crops (47). A venting system of perforated PVC pipes had been installed at the interface of the landfill and Hunter Farm land. Samples taken from the permanent gas sampling stations at Hunter Farm revealed combustible gas extending 200 feet into the Hunter Farm field. It was not possible at the time to determine whether any improvement in gas migration had been effected by the venting system.

Hunter Farm was again visited in December, 1974 when fields planted with rye were growing poorly (47). Gas checks revealed that combustible gases were present in the area of new vegetation injury and that migrating gases were now reaching 600 feet from the nearest edge of the landfill. Apparently the venting was inadequate.

Another trip to Hunter's Farm was made in July, 1975 when corn and sweet potato were found to be growing poorly in areas where combustible gas concentration was high. At this time gas migration was found at 800+ feet from the edge of the landfill (77).

On May 14, 1973, the Rutgers group visited Sharkey's Landfill in Parsippany-Troy Hills, New Jersey to estimate its potential for supporting vegetative cover and to examine field test plots set out by a county agent (51). It appeared that grass seeding had been attempted; however, grass seemed to be growing well over only small areas of the fill. Numerous pools of oily leachate were observed, many with gas bubbles breaking the surface.

Samples of soil gas revealed high concentrations of combustible gases. In the few areas where vegetation seemed to be growing well, there was little, if any combustible gas in the root zone.

The general consensus on the possibility of successful vegetation appeared to be that only shallow rooted species such as grasses would be expected to thrive over most of the area. In some spots devoid of combustible gas it might be possible to grow deeper rooted vegetation.

A communication from the county agent on June 3, 1975 revealed that clover, vetch, lespedeza and weeping love grass were doing well on the landfill (52).

On January 28, 1974 the Rutgers group visited an 18-acre refuse landfill which was the proposed site for a high-rise apartment project. At the north end of the landfill, a bank had been constructed three years previously on pilings (53). Ground settling, gas odor and vegetation death were observed on the bank property. Checks for soil gas revealed high concentrations of combustible gases in the areas of vegetation death.

At the same time that the Rutgers investigations were going on in New Jersey other investigators in this country and abroad were also reporting lack of success in growing vegetation on or near landfills.

In 1972, Kutsuma found a chestnut blight in the area of a landfill in the Toma River Valley in Japan, due to a high carbon dioxide and methane content (54) and the following year Ueshita, Kuwayama and Saita (55) reported the death of unspecified tree species which had been planted on a landfill in Aichi Prefecture.

In 1972, a scientific study of the growth response of four species of pine on simulated landfills was conducted by Cremer (56) in fulfillment of requirements for an advanced degree at Yale School of Forestry. Preliminary results indicated that two of the species, Monterey pine and Pitch pine, were growing poorly on the simulated landfill plot whereas Austrian pine and Jack pine appeared to be unaffected.

In 1973 a report from Toronto, Canada (57) blamed ethylene gas from a landfill for vegetation mortality.

In the same year an anonymous publication (45) issued in Ontario, Canada discussed the killing of vegetation by gases escaping from a sanitary landfill in Mississauga, Ontario.

Various other communications (34, 58, 59, 30) during the past year have reported further observations of vegetation problems on former landfills ascribing the problem to methane gas, high soil temperatures, and/or insufficient depth of cover. Among the reports was one describing injury to corn crops on landfilled trenches as compared to normal growth on inter-trench nonlandfilled areas in Connecticut (60).

The variability in results from efforts to establish vegetation on former landfill sites is apparently due to variability in certain landfill characteristics such as type and amount of solid waste, depth of cover, construction and grading of the fill; certain regional meteorological conditions, such as temperature, relative humidity and rainfall; soil characteristics such as composition, texture, ability to retain moisture, nutritional characteristics; adaptability of plant species to landfill conditions, and planting and maintenance techniques to overcome unfavorable landfill conditions (61, 62, 63, 64, 65, 35).

EFFECTS OF LANDFILL GASES ON VEGETATION

Illuminating Gas

Included among the many decomposition gases from landfills produced during the anaerobic breakdown of organic matter are CH_4, H_2, NH_3, H_2S, CO_2, N_2, C_2H_4, and CO (66). Mechanisms have been brought forth to show how these products are formed from their precursor macromolecules. The literature describing the effects of these gases on vegetation is very sparse possibly due to the lack of concern. However, as far back as 1807, problems concerned with trees injured by illuminating gas accidently leaking into the soil, may be said to have commenced when the first public street lighting system was installed in Pall Mall, London (67).

One may ask what illuminating gas has to do with these decomposition gases and their effects on vegetation. Table 1 gives the composition and some representative concentration of the constituents of illuminating gas. A quick glance at this chart will bring forth immediately, the importance of studying the effect of illuminating gas on vegetation. The gases CH_4, CO_2, N_2, C_2H_4 and CO comprise the majority of the constituents of manufactured illuminating gas.

TABLE 1. APPROXIMATE PERCENTAGES OF SUBSTANCES COMPRISING MANUFACTURED ILLUMINATING GAS

Substance	% Composition by Volume
Ethylene (C_2H_4)	3
Acetylene (C_2H_2)	5
Benzene (C_6H_6)	
Butylene (C_4H_8)	
Propylene (C_3H_6)	
Carbon Monoxide (CO)	33%
Ammonia (NH_3)	Less Than 5%
Cyanogen compounds*	
Hydrocyanic Acid* (HCN)	
Hydrogen (H_2)	33
Carbon Dioxide (CO_2)	1.5
Oxygen (O_2)	1
Nitrogen (N_2)	6
Methane (CH_4), ethane (C_2H_6), propane (C_3H_8)	12

*Most of these have been removed from manufactured gas by a process called "scrubbing".

NOTE: This table was abstracted from bibliography reference #70.

Ethylene (C_2H_4) is of special interest although it has to date rarely been considered a limiting factor by authorities trying to establish vegetation on completed sanitary landfills. Smith and Restall (68) showed that ethylene was produced in anaerobic soil by biological activity and not by chemical action. In a simulated anaerobic soil, when O_2 concentrations fell to zero, ethylene production increased. Total evolution was related to organic matter content and soil temperature. A temperature of 35°C produced the maximum ethylene evolutions.

Methane production was also reported to be optimum at 30°C and 35°C by Dobson and Ramswany respectively (25, 20). Smith and Harris (69) report that under anaerobic conditions, if no losses of ethylene occur, its concentration in soil atmosphere can reach or exceed 20 p.p.m. (0.002%) in widely differing soil types in the United Kingdom. These concentrations are in considerable excess of those which have been found to cause severe reductions in the extension of seminal root axes in temperate cereals (68). Barley, which was the most sensitive of the cereals studied, suffered 50% reduction in size after three days exposure to 1 p.p.m. of ethylene in soil and 80% at 10 p.p.m. The corresponding figures for rye were 25% and 40%. Oat and wheat sensitivities were between barley and rye. When CO_2 concentrations in the soil were varied, little change in the cereals' response was noted.

Because of the above experiments, it is appropriate to consider ethylene as a possible toxic component of illuminating gas. The late 1800's and early 1900's produced much concern over escaping illuminating gas and the injury it caused when in contact with the root system of various shade trees and ornamentals. The historical portion of Crocker and Knight's (71) study on carnations and illuminating gas described much of the previous work done in Germany in the late 1800's. According to Crocker and Knight Kny was one of the first to test the injury experimentally. He used three sound trees in the Berlin Botanical Garden, each about twenty years old--one maple (Acer) and two lindens (Tilia). Gas pipes were laid 84 cm. underneath the soil where these trees were to be planted. On July 7 illuminating gas was passed through the pipes beneath the maple at 12.9 cu.m./day and beneath the two lindens, 11.7 and 1.6 cu.m/day respectively. First a euonymous (E. europea) bush near the maple died, followed by defoliation of the maple leaves on September 1. An American elm near by showed injury also. On September 30, the first linden began to show signs of injury, and by October 12 it had lost all its leaves. The second linden had lost its leaves by October 19. A blue discoloration concentrated in the stele showed up on close examination of cross sections of the roots one-half inch in diameter or larger. The lindens both produced foilage the following spring; however, it was bleached and very stunted. The maple, elm, and euonymous bush showed no signs of life.

Spath and Meyer (71) passed 1 cu.m. of gas daily through wooden pots each containing one tree. Platanus, silver poplar, American walnut and Ailanthus were killed; maple and horse chestnut were severely injured, and a linden showed no injury. The leaves of the injured trees were a pale green or yellow and most of the younger roots were dead. These investigators concluded that trees are far less sensitive to gas injury during the winter months when the sap is not flowing than during the growing season. The above two experiments suggest that linden is more resistant to injury brought about by illuminating gas than any other mentioned species.

Bohm (71) grew slips of water willow in water through which gas was passed. He found that they produced only short roots and that these soon died, as did the dormant buds. The twigs themselves remained alive for about three months until, as he believes, the reserve food had been exhausted.

In another experiment he found that soil impregnated with gas was very poisonous to plants and for seed put to germinate in it. A draceana planted in such soil died in ten days. Far less injury was shown when a given quantity of gas was in contact with the portions of the plant above the ground than when the same quantity came in contact with the roots by being passed into the soil. He concluded that roots are most sensitive to gas injury.

Wehmer (71) calls attention to a severe case of gas poisoning in Hanover, Germany. Thirteen elm trees along a street showed injuries varying with the distance they stood from a leak in a gas pipe. In late winter a number of them showed brown discoloration of the inner bark, and a falling-off of the bark in very large patches extending up the trunk six feet from the ground. No blue discolorations of the roots appeared as was reported by Kny (71) and other observers (71).

Molisch (71) found that growth in length of roots is retarded by 0.005% illuminating gas in soil gas atmosphere. If uninjured and decapitated roots of corn are grown in illuminating gas, the former are remarkably bent and retarded in their growth in length, while the latter grow almost straight and are comparatively vigorous. Under the influence of the gas the growth in thickness of the roots is increased with the greatest thickening occurring where the bending is sharpest.

Shonnard (71) had exposed potted lemon trees to gas at 1.07 cu. ft./hr. constantly for eight days when he noted exudation of sap in considerable quantity from the trunk and branches, as well as chlorosis and defoliation of leaves. He found gametophytes of certain mosses to be very resistant, suffering very little injury in high concentrations of these gases after two months exposure. Elodea and nittella's older cells were injured to a greater extent than the younger cells, as shown by the plasmolysis of the cells.

Richards and Mac Dougal (72) found that carbon monoxide and illuminating gas retarded the rate of elongation of roots of Vicia faba, sunflower, wheat and rice. Swelling also appeared in the leaf sheaths of wheat, being somewhat more pronounced with illuminating gas than with carbon monoxide. Examination of a root cross section under an appropriate microscope showed that these increases in root diameter were largely due to the enlargement of the cortical cells.

Stone (73) has reported proliferations of tissue at the lenticels of willow slips growing in water which had been charged with illumination gas. He also noted a rapid proliferation of the cambium in stems of Populus deltoides (Quaking Aspen) under the influence of illuminating gas.

Probably one of the most extensive studies carried out to investigate the effects of illuminating gas on vegetation was done by Harvey and Rose (74). This investigation was undertaken with two objectives in mind: 1-to determine some of the effects of illuminating gas on root systems, and 2-to determine whether the chief causes of injury are those constituents of illuminating gas which are readily absorbed by the water film of soil particles or those which remain primarily in the soil interstices. Because previous work had pointed out the "ethylene effect" on trees which were exposed to illuminating gas, Harvey and Rose (74) decided to test this hypothesis. They placed the bare roots of six Vicia faba seedlings inside a large humidified glass bottle into which they pumped illuminating gas. Then, using the same species in soil and exposing the soil to similar concentrations of gas, they produced the same response as observed with the bare roots. Therefore, they concluded that the constituents of illuminating gas which are relatively insoluble in water are responsible for the response in Vicia faba. Ethylene is included as an insoluble gas. This fact further stimulated Harvey et al. to move towards testing ethylene toxicity.

Again, they used Vicia faba and exposed bare roots, as described above, to illuminating gas. In a separate bottle, ethylene, in concentrations corresponding to that in the illuminating gas, was passed around the roots of the same species. From the observations made in these tests the ethylene was considered one of the toxic agents present in illuminating gas.

The concentration of ethylene used here was 0.001% or 10 p.p.m. Barley's growth decreased by 50% at 1 p.p.m. and rye responded to the same concentrations by a 25% decrease (69). In all these cases, the root response to gas exposure was a bending and swelling of the root at this bend.

When the roots of radish, mustard, and tomato seedlings were exposed in a moist-air chamber to illuminating gas for 24, 48, and 72 hours respectively, the responses of the tomato differed from that of the radish and mustard seedlings(74). While the roots of the mustard and radish showed obvious signs of bending and swelling very similar to Vicia faba, the tomato roots grew as straight as normal seedlings' roots. However, swelling of the hypocotyl was evident and was found to be the result of an enlargement of the cortex and phellogen. Close examination of the stele showed no structural differences from that of a control tomato plant. The experiments with ethylene on tomato again gave some evidence that the toxic effect recorded for illuminating gas is due to the ethylene constituents of that gas.

When Catalpa speciosa seedlings were exposed for eight days to illuminating gas piped through the soil at concentrations of 0.05, 0.5, 2.5 and 5%, stems and leaves showed no modifications (74). However, at 2.5 and 5% the roots showed very obvious swelling. When the same species were exposed to ethylene concentrations of 0.002, 0.02, 0.1, and 0.2% which is comparable to the amount of ethylene contained in the illuminating gas used above, the response shown by the 0.1 and 0.2% ethylene was like that shown by 2.5 and 5% illuminating gas. This gave further evidence to the expanding theory that ethylene toxicity is responsible for the response of the root systems to the illuminating gas. This also showed that larger quantities of illuminating gas and ethylene are needed in soil to produce the same response by roots exposed to corresponding quantities of gas with no soil. Possibly the soil is acting as a buffer and is either absorbing or utilizing the ethylene.

When Catalpa seedlings were exposed for twenty-one days to illuminating gas concentrations of 25% (1% ethylene) a swelling of the main root appeared (6). The increase was 2-3 times that of the normal thickness. The epidermis was often cracked and sloughed off in places. Such cracks provide root rotting fungi and bacteria a mode of easy entry into the root. Very serious stunting and even death can result from root rot infections especially when attack is promoted against young seedlings (75).

Ailanthus altissima seedlings were exposed by Harvey and Rose (74) for fifteen days to illuminating gas concentrations of 0.25 and 10%. The 0.25% treatment gave slight swelling of the roots 3-4 cm below the surface, while the 10% treatment produced leaf drop beginning five days after the gassing commenced. By the end of the experiment, all leaves had fallen. When ethylene was used instead of illuminating gas, in concentrations corresponding to the amount of ethylene present in the illuminating gas in the above experiment, very similar responses were observed. The lower ethylene concentration(0.01%) produced negligible swelling while the higher concentration (0.4%) produced swollen top roots and leaf drop, eight days after the gassing started. Through the examination of cross sections of the control plants and gassed plants, it became evident that the stelar region had remained unchanged, while the cortex, extending into the phellogen layer, had increased in thickness, partly through the increase in cell diameter and partly through cell division. This same phenomenon was seen in the gassed tomato and the Vicia faba plants (74).

A number of tests were carried out with Gleditsia (Locust) seedlings (74). Illuminating gas in concentrations up to 33% were used to fumigate the roots. These high concentrations gave leaf drop, but no definite injuries were detected in the root system.

Briefly looking back on the above work brings out an interesting trend in the pattern of damage produced by varying the concentrations of illuminating gas and ethylene gas in the soil. At low concentrations, such as with the radish and mustard experiment and the Vicia faba plants, the response seems to be primarily a swelling of the roots. However, when higher concentrations are provided to the root systems, the response seen in the root system is cracking and sloughing off of the epidermis in Catalpa. Ailanthus and Gleditsia responded to higher concentrations by dropping their leaves.

Harvey and Rose (74) summarize the work carried out by Kosaroff, whose experiments found that the symptoms manifested in the aerial parts of plants due to illuminating gas being passed through the soil were similar to those seen where the plants were exposed to droughty conditions. He further states that injury is not necessarily due to conduction of toxic substances into the leaves; however, this possibility is not to be overlooked. In experiments conducted to determine the effect various transpiration rates had on the plants' response to gas exposure, Kosaroff found that greater evapotranspiration rates produced gas type injury sooner than did lesser rates of evapotranspiration.

A final experiment was conducted by Harvey and Rose (74) with an Ailanthus tree having an 8 cm diameter and a 3.5 meter height. They used many surrounding Ailanthus trees as controls. By placing a glass tube 0.7 meters into the soil and 0.6 meters from the tree, they passed illuminating gas to the roots of this Ailanthus tree. The gas was supplied at a relatively constant rate starting on July 3. The first symptoms of injury were manifested on July 14. The leaves of some of the young shoots growing on the side of the tree where the gas entered the soil, showed signs of wilting. Three days later these leaves and others shriveled and died, but remained attached to the branches. In the middle of September, the leaves which were apparently unaffected initially, began to shrivel and fall. This tree had lost all its leaves much sooner than the nearby controls. In our field work we have observed black cherry (Prunus serotinia) and black oak (Quercus velutina), apparently killed by landfill decomposition gases, whose leaves had shriveled and still remained hanging on the branches.

In the early 1900's quite a number of articles were written, which reported and described illuminating gas kill of vegetation. Two of the more in depth set of observations were made by members of the Massachusetts Agriculture Experiment Station in 1907 and 1913. In both cases observations were made on a number of trees over an extended period of time beginning with the time of first known gas exposure. Some of their results are discussed below.

Stone (75) reports that the poisonous properties of illuminating gas are largely confined to the numerous products which are absorbed by the soil moisture in small quantities, taken up through the roots and translocated through the tissue. This is in conflict with Harvey and Rose (74) who carried out a controlled experiment showing quite conclusively that the gases present in the interstitial spaces in the soil were responsible for the toxic effect of the gas on vegetation. Stone gives no data for his statement. Stone further states that these substances are to be found in the tissue; however, the response differs between species and even with different parts of the plant.

An anonymous report (66) by the Massachusetts Agriculture Experimental Station describes gas injury in two classes: first incipient cases, then pronounced cases. During observation of the incipient cases the bark has been seen peeling off in very large strips, up to 6 feet long in American elm (66) and 2.5 feet long in quaking aspen (Populus deltoides) (73). The bark on the sides of these cracks was bulged out considerably and on closer examination it was shown that a thick layer of soft parenchymous tissue extended into the wood for a considerable distance. This abnormal tissue was formed outside of the cambium from which it seemed to have been derived. Remember that Harvey and Rose (74) observed A. altissima leaves turning yellow first, then dropping off. The leaves farthest from the source of water, i.e. those at the top of the tree and the ends of the branches, have been observed to be the first leaves to show signs of injury. These are the leaves which characteristically will be the first to show signs of water deficiency. It is the work by Harvey and Rose (74) and others (67) which leads to the belief that root damage at least plays a small role in the yellowing of the leaves farthest from the roots and water supply.

Following the initial injury to the foliage are characteristic changes in the wood and bark of the tree as was briefly mentioned above. The first symptoms appear as a drying of the cambium and other tissues outside the wood or xylem. Later these tissues (cambium, phloem, and cortex) turn brown and disintegration follows. These abnormal conditions first take place in the roots, but Stone states that later, as translocation proceeds, the poisonous constituents may be detected in the wood in the above-ground parts. A characteristic odor can be detected in a cut section of the trunk after the roots have been exposed to gas (66). Following disintegration of the phloem, cortex, and cambium there is a change in the physical properties of the bark, causing it to dry out and crack open, exposing the underlying tissues (66, 73). This may soon be followed by fungal and bacterial invasion. Species of fungi in the genera Polystictus and Schizospyllum have been isolated as well as the bacterium Penicillium. A complicated process of wood decay follows which soon makes the wood unsalvageable even for firewood (75).

Stone (73) makes a final statement concerning the symptoms observed following gas exposure of the roots. He states, "All the conditions refer merely to the way in which a tree succumbs to gas poisoning, and do not necessarily constitute reliable symptoms of this type of injury, as these symptoms may be found in trees dying from other causes. The tissue furnishes the most reliable symptoms for diagnosis."

Stone (73) has carried out a study, to observe the effect of illuminating gas upon vegetation when provided to the above ground parts. He observed that Kenilworth ivy, papyrus, tobacco, tomato and others were damaged, while ferns, mosses and liverwort were hardly affected. He suggests that because the latter group have evolved in time much earlier than the former, that they are tolerant to a wider range of gas exposure. If this holds true, species such as palm and ginkgo tree would be more tolerant to illuminating gas exposure to above ground portions than modern deciduous and conifers, e.g. black cherry, red oak, white spruce, etc.

In the spring and summer of 1934 Deuber (67) carried out an experiment with the purpose of recording the influence of various rates of flow and quantities of a typical manufactured gas on the growth of three-year old American elms (Ulmus americana). These trees were growing in clay pots and were transplanted just before gas exposure to pots containing one liter of soil. Unlike the work described up to this point, this manufactured gas contained no ethylene. Table 2 contains an analysis of the gas used. In addition to the gassed trees, controls were transplanted and handled in a similar manner.

TABLE 2. ANALYSIS OF COKE OVEN GAS SUPPLIED BY NEW HAVEN GASLIGHT COMPANY

Substances	% Composition by Volume
Carbon Dioxide (CO_2)	1.70
Illuminants	3.00
Oxygen (O_2)	0.20
Carbon Monoxide (CO)	8.70
Hydrogen (H_2)	51.00

(continued)

TABLE 2. (continued)

Substances	% Composition by Volume
Methane (CH_4)	25.90
Nitrogen (N_2)	10.0
Naphthalene ($C_{10}H_8$)	3.5
Sulphur (S)	trace
Hydrocyanic Acid (HCN)	--

NOTE: Obtained from reference #67.

He exposed ten elm trees to various gas flow rates and various quantities of total gas supplied. The earliest symptoms observed were chlorosis of the leaves and defoliation. Chlorosis generally involved the leaf margins first and sometimes proceeded no further. Usually the lower-most leaves on the main stem or larger branches became chlorotic and abscised before the younger upper leaves. This is in direct conflict to the pattern seen when trees were gassed with illuminating gas containing ethylene (74). The trees receiving the highest quantities of gas in the shortest period of time became defoliated within five days. However, both trees produced an enormous amount of new shoots within a month. The condition of these new shoots was unreported at this time. The trees supplied with lesser amounts of gas gave a variety of responses ranging from gradual defoliation over a three month period to slight chlorosis. The tree in soil through which 7 cu. ft. of gas had been passed continued to be normal in appearance except for a slight chlorosis at the bases of three leaves. The following spring, these trees exhibited normal growth of tops and roots. Deuber (67) has discussed in this same paper his personal observation of trees apparently injured by root exposure to illuminating gas leaks. He states, "Rapid killing of a shade tree within a few days or a few weeks has been seen occasionally, but the more numerous cases are those in which chlorosis of the foliage on a portion of the tree and partial defoliation is subsequently followed by the drying out and death of uppermost twigs, and the drying of some branches and not others."

Other experiments carried out by Deuber in which woody plants were subjected to a "mixed illuminating" gas and, in some instances, to ethylene, led him to describe three classes of plant physiological responses to this illuminating gas. The first response is stimulation, such as accelerated development of latent buds and proliferation of root parenchyma. The second class of responses is injury, such as inhibition of bud development and dwarfing of leaves. The third response is killing effects, ranging from partial to complete defoliation. The type and degree of the physiological response of small elm trees varied with time of exposure (season) and with the part of the plant exposed to the gas i.e. roots or leaves.

Deuber (67) worked with ethylene in concentrations of 1% to 5% in air held about the bases of rooted cuttings of privet or small oak trees and observed chlorosis, defoliation, and drying out of the leaves on the top of the plants. He has concluded from this and his above experiment with illuminating gas that "ethylene or gaseous ingredients of similar physiological action on plants can explain the symptoms observed when relatively large volumes of the coke oven gas employed in this investigation are passed into the soil in which small elm trees are growing".

SUMMARY

The deleterious effects of illuminating gas on many species of plants have been observed, demonstrated, and reported frequently since the early nineteen hundreds. A few species have also been reported to be relatively tolerant to the presence of illuminating gas in their root zone. Tables 3 and 4 list these tolerant and sensitive species as reported in the literature.

TABLE 3. PLANT SPECIES RELATIVELY TOLERANT TO ILLUMINATING GAS AS REPORTED IN THE LITERATURE

Common Name	Genus-Species
Birch (71)	*Betula*
American Linden (71)	*Tilia americana*
Rough Fruited Maple (71)	*Acer sp.*
Norway Maple (76)	*Acer platenoides*
Privet (67)	*Ligustrum*
Mosses (70)	
Ferns (70)	
Liverworts (70)	
Locust seedlings (74)	*Gleditsia sp*

TABLE 4. PLANT SPECIES RELATIVELY SENSITIVE TO ILLUMINATING GAS AS REPORTED IN THE LITERATURE

Common Name	Genus-Species
Sycamore (71)	Platanus
Silver poplar (71)	Populus
American Walnut (71)	Juglans sp
Tree of Heaven (71)	Ailanthus altissima
American Elm (70, 71)	Ulmus americana
Dracaena (71)	Dracaena
Horsechestnut (71)	Aesculus hippocastanum
Alder (70)	Alnus
Apple (70)	Malus
Ash (70)	Fraxinus
Boxelder (70)	Acer negunda
Catalpa (70, 67)	Catalpa bignonioides
American Linden (70, 67)	Tilia americana
Pear (70)	Pyrus
Poplar (70)	Populus
Euonymous (71)	Euonymous europea
Willow (67)	Salix
Cherry (67)	Prunus
Silver Bell (67)	Halisia caroliniana
Red Oak (67)	Quercus rubra
Black Oak (67)	Quercus velutina
Bermuda grass (74)	Cyndon dactylon
Fuchsia (71)	Fuchsia
Salvia (71)	Salvia splendens

In most of the studies where gas was injected into the root zone the leaves dried. Trees growing in the vicinity of illuminating gas line leaks have exhibited similar symptoms as well as bark-peeling and tissue-staining. Ethylene has been demonstrated to be one of the prime factors involved in the toxic effect of illuminating gas on vegetation in very minute quantities.

Effect of Carbon Dioxide on Plant Growth

Since carbon dioxide can be produced in the refuse and in the soil saturated with methane an investigation into what effects this could have on plant growth is in order.

In our field survey concentrations of carbon dioxide in the soil ranged from less than 1% to 34% of the soil atmosphere. A large percentage of these readings were in the 5% to 15% range (77). Normal soil carbon dioxide usually ranges from 0.04% to 2% (17); therefore, the levels recorded in the survey are excessive.

In 1914 H. A. Noyes saturated the soil around tomatoes and corn plants with carbon dioxide. Both species died in two weeks but there was no irreversible damage to the soil (16). Ruben and Kama in 1940 demonstrated the uptake and fixation of carbon dioxide by barley roots. They used a radioisotope tracer to show this but were unable to isolate the products of fixation in the plant (78). This was done in 1953 by Poel who identified the products of fixation as citric, aspartic and glutamic acids, serine, asparagine, glutamine, tryosine and alpha-keto-glutaric acid (79). Stolwijk and Thimann in 1957 found that the products of carbon dioxide fixation in the roots of pea seedlings were transported to the shoots. They also found that concentrations of 0.5% carbon dioxide stimulated root growth but 1% carbon dioxide inhibited root growth (80). Geisler found that exposing pea seedlings to 5 to 250 milligrams of CO_2 per liter in a hydroponic solution stimulated root growth (81). The stimulation noted was in root elongation; the roots were thinner and an increase in the rate of lateral root initiation was also noted. This stimulatory effect of low levels of carbon dioxide were attributed to the ability of the roots to use it as a carbon source. In light of more recent developments it seems more likely that the carbon dioxide is competing with ethylene for a receptor site. This competition results in a more pronounced auxin response. Increased cell elongation would be characteristic of this hormonal imbalance (82).

There has been a lot of work done on establishing tolerance in various species to excess carbon dioxide in the root zone A good deal of variation in tolerance between species has been found. Cotton seedlings grown in hydroponic solutions were able to exhibit optimum growth with 10% carbon dioxide present, provided at least 7.5% oxygen was also present. Thirty to forty-five percent carbon dioxide was found to severely reduce root growth (17). Red and black raspberries were killed when their roots were exposed to 10% carbon dioxide. The root growth in the species, Pisum sativum, Vicia faba and Phasedus vulgaris, was completely inhibited by 5.5% carbon dioxide (18).

The ability of carbon dioxide to disrupt the normal function of root cells was investigated by Norris, Weigand and Johanson in 1959. Excised onion root tips were exposed to an atmosphere of 90% oxygen and 10% carbon dioxide. The rate of respiration was halved and when the same tissue was flushed with pure oxygen the rate continued to halve. This was attributed by the authors to be due to permanent damage to the cells caused by dissolved carbon dioxide lowering the pH (19).

Effect of Low Oxygen on Plant Growth

Low concentrations of oxygen have been reported in the soil near natural gas leaks (13). A similar situation has been found both on and adjacent to sanitary landfills. In this study oxygen concentrations in the soil on landfills were found to range from 1% to 20% of the soil atmosphere (77).

In 1945, Chang and Loomis conducted a general survey of the literature and concluded that plants would survive concentrations of oxygen in the root zone of one to two percent. They also concluded that most plants should function normally at oxygen concentrations ranging from five to ten percent (83). There is, of course, a good deal of variability between the different species in their tolerance to low oxygen concentrations in the root zone. Orange tree roots stopped growing when oxygen levels were between 1.2% and 5% and were retarded at concentrations of 5% to 8% at 28°C (84). Apple trees were found to require 10% oxygen for good growth to occur but they could survive concentrations as low as 0.1% (85). Ten percent oxygen was found to inhibit the growth of both red and black raspberries (18).

Higher temperatures were found to increase the need for oxygen in growing roots (18). A dense soil will also increase the need for oxygen at the growing root tip. This is believed to be due to the extra work that has to be done by the root tips as they push their way through the soil (86).

Sustained low oxygen concentrations in the soil have been found to result in mineral deficiency symptoms in the plant. Potassium is usually the first to occur and it is followed in order of appearance by nitrogen, phosphorus, calcium and magnesium (87, 88).

EFFECTS OF LANDFILL GASES ON SOIL QUALITY

In investigations of the effects of natural gas (methane) leaks on physical properties of soils, several investigators (89, 13, 90, 15, 91) reported increases in pH, organic matter, available phosphorus, calcium, potassium, iron, manganese, nitrate-nitrogen, ammonia-nitrogen, and moisture content in areas around the gas leaks as compared with normal soil away from the leaks. In some cases the fertility of the soil was increased by leaking gas to the point that crops such as wheat and oats grew better on the gassed soils than on normal soils (90). The fact that the ratio of organic matter to nitrogen was generally lower in the gassed soil led to the conclusion that the soil alterations were probably due to the activity of micro-organisms under anaerobic conditions.

The reason for the observed increases in concentrations of nitrogen compounds and trace elements in gassed soils undoubtedly lies in the low redox potential of these soils, as has been documented for similar responses of soil to flooding conditions (92, 93, 94). When oxygen disappears from the soil, requirements of anaerobic soil microorganisms for a source of oxygen results in the reduction of several oxidized compounds namely nitrate, nitrite, and the higher oxides of manganese, and iron. These reduced forms are generally more soluble and hence are made available to plants. Availability of other trace metals occurs as they are displaced by ferrous ions from the exchange complex to the soil solution.

The trend to neutrality in pH is probably caused by the buffering effect of organic acids released by the microbial breakdown of organic matter.

The consequences of these soil changes in landfills have yet to be evaluated. At this time it is considered that these soil conditions contribute to the damage done to vegetation, although to a lesser degree than does the presence of landfill gas. However, the presence of ammonia-nitrogen or of trace elements in toxic concentrations might hasten the death of vegetation already debilitated by the presence of toxic gases and/or the lack of oxygen in the root atmosphere.

SECTION V

NATIONAL SURVEY OF PROBLEM

MAIL SURVEY OF VEGETATION PROBLEMS ASSOCIATED WITH REFUSE LANDFILLS

Procedure

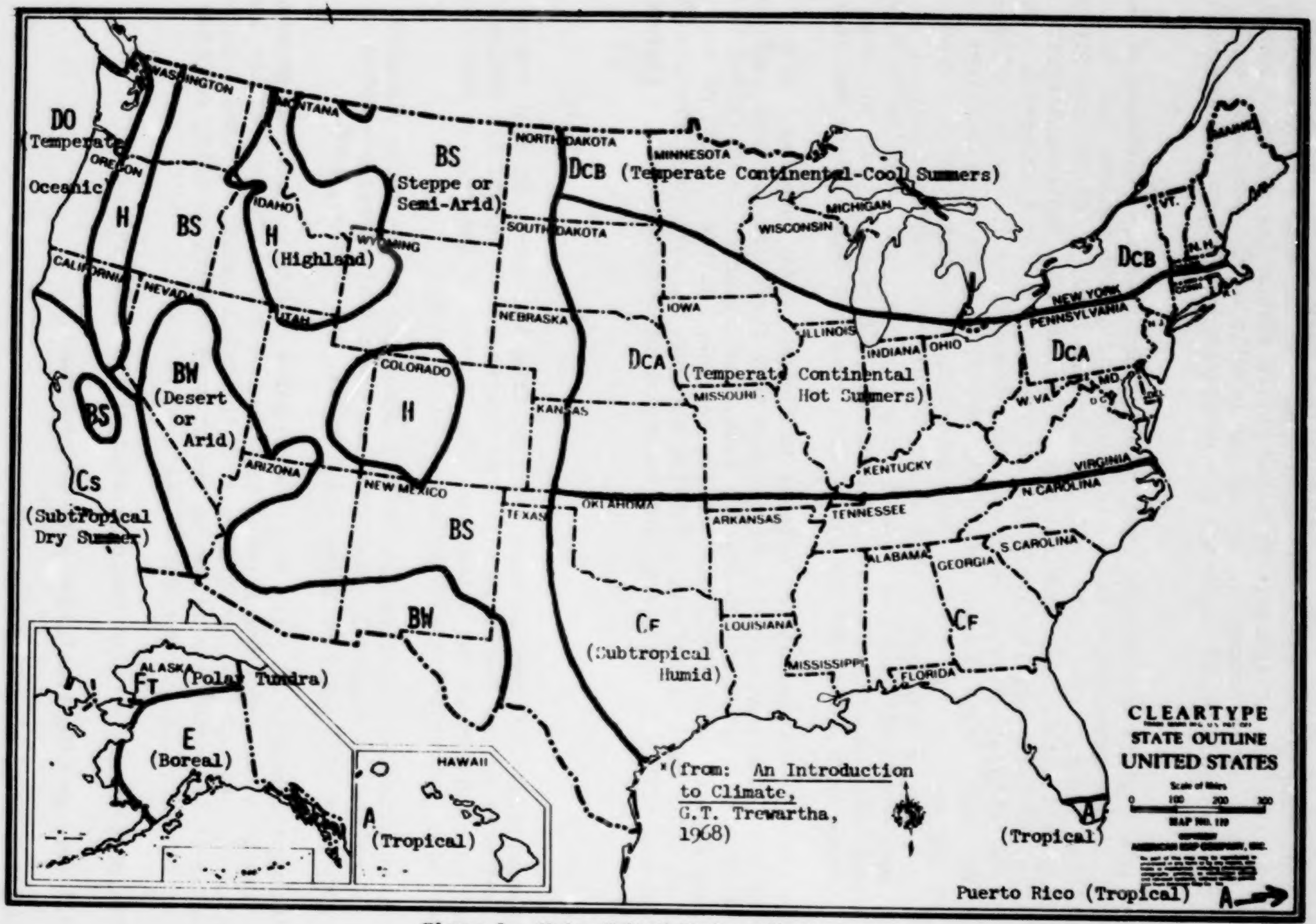
The investigation to determine the geographic extent of problems associated with growing vegetation on completed landfills was conducted in two stages, the first of which was a mail survey for the purpose of obtaining preliminary information on the location of and the vegetative condition of former sanitary landfills which have been converted to parks, playgrounds, golf courses or other types of recreational areas.

On the basis of information obtained through the mail survey, specific landfills were selected for site visits, so that the nine climatological regions of the United States and territories (Figure 1) proposed by Trewartha in his textbook entitled An Introduction to Climate were covered.

Approximately 1,000 letters were sent to people and publications throughout the United States explaining that we were undertaking a survey to determine the extent of problems associated with growing vegetation adjacent to, and on top of completed solid waste refuse landfills.

Appendix A is a copy of the basic letter sent to most of these people. A total of seven differently worded letters was sent. However, a majority of the people receiving the letters of inquiry received the basic letter. Most of the other six letters contained only slight modifications of the letter in Appendix A. The modifications were made to accommodate the different audiences. The letter in Appendix A was reproduced by the Itek system. The address and salutation for each letter recipient were individually typed and each closing signature was individually written. In cases where the letter sender, Franklin B. Flower, personally knew the recipients of the letter, an additional personal postscript was added to the letter to encourage their response.

A questionnaire (Appendix B) and a stamped, self-addressed envelope were enclosed with each letter. The questionnaire requested the names and addresses of landfills which have had problems growing vegetation above them or adjacent to them and the names and addresses of landfills which have been successful in growing grass, shrubs, trees or other vegetation. Comments on the effects of buried refuse on living surface vegetation were also sought. The enclosed self addressed, stamped envelope enabled the recipient to easily return the questionnaire. The questionnaire was designed so that it would


DO
(Temperate
Oceanic)
H
BS
H
(Highland)
BS
(Steppe or
Semi-Arid)
DcB (Temperate Continental-Cool Summers)
DcB
DcA
(Temperate Continental
Hot Summers)
DcA
BW
(Desert
or
Arid)
BS
Cs
(Subtropical
Dry Summer)
H
BS
BW
CF
(Subtropical
Humid)
CF
A
(Tropical)
FT (Polar Tundra)
E
(Boreal)
ALASKA
HAWAII
A
(Tropical)
Puerto Rico (Tropical)
A
WASHINGTON
OREGON
CALIFORNIA
NEVADA
IDAHO
MONTANA
WYOMING
UTAH
ARIZONA
COLORADO
NEW MEXICO
NORTH DAKOTA
SOUTH DAKOTA
NEBRASKA
KANSAS
OKLAHOMA
TEXAS
MINNESOTA
IOWA
MISSOURI
ARKANSAS
LOUISIANA
WISCONSIN
MICHIGAN
ILLINOIS
INDIANA
OHIO
KENTUCKY
TENNESSEE
MISSISSIPPI
ALABAMA
GEORGIA
FLORIDA
S CAROLINA
N CAROLINA
VIRGINIA
W VA
MD
D C
PENNSYLVANIA
NEW YORK
N J
VT.
N.H.
CONN
R I
MAINE
CLEARTYPE
STATE OUTLINE
UNITED STATES
Scale of Miles
0 100 200 300
MAP NO. 119
AMERICAN MAP COMPANY, INC.

*(from: An Introduction to Climate, G.T. Trewartha, 1968)

Figure 1. Major United States climate types*

Reprinted with permission of the American Map Company, Inc.

take a minimum amount of effort to complete but would supply information which would enable us to locate those refuse landfills which showed the best and poorest vegetation growth associated with them. We included a notation that could be check-marked to indicate that the person completing the questionnaire would like to obtain a summary report of the results of the completed study. It was felt that this would encourage the recipient to complete and return the questionnaire.

Appendix C lists the sources from which we obtained the addresses of the recipients of the questionnaires and the number of questionnaires sent to each of these groups. The State Soil Conservation Service Office, the Director of the Cooperative Extension Service, and the Solid Waste Management Office in every state and territory received this written request for information. The thirty-three publications with which we communicated were the major publications of the solid waste management field. Mailing of the questionnaires to people on the various registration and membership lists was done on a selective basis. The 130 mailings listed under "other" included consultants; landfill operators; directors of county, city and municipal solid waste management programs; educators; etc. The names and addresses of many of these "other" people were obtained from the replies received from earlier mailings.

The State Soil Conservation offices in Alabama, Iowa, and Texas made copies of our letter and questionnaire which they forwarded to their regional (county) offices. After assembling the data, they returned to us either the individual replies or a compilation of the replies. At the request of the individual State Soil Conservation Service offices, we sent questionnaires to each regional office in New Jersey and to twelve of New York State's regional offices.

Results

Approximately 500 replies were received from the survey in addition to the 40 returned by the Post Office as undeliverable. Of these, 115 indicated they had no knowledge of the situation. The balance of the replies contained information on approximately 500 refuse landfill sites.

The results are summarized in Table 5 according to the major climatic zones as outlined in Figure 1, which follows the climate types presented in An Introduction to Climate by Glen T. Trewartha, 4th edition, 1968.

Adding the number of sites reported in Table 5 with no problems growing vegetation to those reporting growing problems on and/or adjacent to the landfill gives a total of 544, or 37 more than the total number of sites reported. This apparent inconsistency is due to two or more conditions being reported to exist concurrently at some landfills.

The mail survey results indicate that of the sites reporting:

76% were growing vegetation without problems;

25% had problems growing vegetation on the soil cover;

7% were experiencing difficulty in growing vegetation adjacent to the landfill;

17% were successfully growing trees on the landfill;

63% grew grass successfully on the landfill;

12% grew shrubs successfully on the landfill.

No significant difference was noted in the degree of problems reported from landfills located in the different meterological zones (Table 6). Sixteen or more reports were received from each of the five climatic zones. Of these, the percent of sites reporting no growing problems ranged from 72% to 77% and the percent reporting some kind of vegetative growth problem varied from 30% to 48% of the total number of sites reporting. Table 7 summarizes the results by states.

Thirty-eight replies commented on the possible causes of vegetation growth problems on refuse landfills and what should be done about them. The most frequently reported suggestions and the percent of people reporting each suggestion were:

47% - Use or develop a good quality soil and good cultivation practices;

32% - Landfill gases inhibit vegetation growth;

32% - Use more than two feet of cover for good vegetation growth;

26% - Grow grass or other shallow-rooted crop;

13% - Vent or block landfill gases to keep them away from the root zone of vegetation;

11% - Consider adaptable species;

11% - Leachate causes vegetation growth problems;

11% - Well-compacted refuse will enhance vegetation growth;

11% - Good surface drainage enhances vegetation growth.

While the major reason reported for poor vegetation growth was the lack of good soil and/or poor cultivation practices, a high percentage of those reporting did give the presence of landfill gases as a major cause of this poor growth. Others suggested various methods for keeping the gases away from the root zone of vegetation as an aid to better growth.

Although we have been able to produce very nice tables from the data obtained from the mail survey, the degree of accuracy of this data is suspect. In the section of this report which gives the results of the field visits

TABLE 5. LANDFILL VEGETATION GROWTH RESULTS BY CLIMATIC ZONE AS REPORTED IN MAIL SURVEY

Major Climate Zone		Total Number With No Problems	Growing				Vegetation Growing Problem		Total # Sites Reported
Symbol	Name		Grass	Shrubs	Trees	Other	Adjacent to Landfill	On Covered Landfill	
Cf	Subtropical Humid	83	70	8	24	10	3	32	112
Dcb	Temperate Continental Cool Summers	25	16	2	5	2	2	8	33
Dca	Temperate Continental Hot Summers	223	192	36	41	22	24	63	291
BS	Steepe or Semi-Arid	13	8	--	1	1	2	6	18
Cs	Subtropical Dry Summer	18	13	12	12	--	2	10	25
Bw	Desert or Arid	2	1	--	--	--	--	--	2
Do	Temperate Oceanic	8	7	--	3	--	--	2	9
H	Highland	6	6	--	--	--	--	1	6
Aw	Tropical Wet and Dry	--	--	--	--	--	--	--	0
Ar	Tropical Wet	--	--	--	--	--	--	1	1
A	Tropical (Hawaii)	6	6	4	2	--	--	4	10
	TOTAL	384	319	62	88	35	33	127	507

TABLE 6. COMPARISON OF VEGETATION GROWTH PROBLEMS BY CLIMATIC ZONES

Major Climate Zone		Number Stations Reporting	Percent - No Growing Problems	Percent - Problems Growing Veg. on Landfill	Percent - Problems Growing Veg. Adjacent to Landfill
Symbol	Name				
Cf	Subtropical Humid	112	74	29	3
Dcb	Temperate Continental Cool Summers	33	76	24	6
Dca	Temperate Continental Hot Summers	291	77	22	8
BS	Steppe or Semi-Arid	18	72	33	11
Ca	Subtropical Dry Summer	25	72	40	8

TABLE 7. RESULTS OF MAIL SURVEY BY STATES AND TERRITORIES

	No. Problems	Problem Adj.	Problems On	Total No. Sites Reporting
Alabama	17	0	14	31
Alaska	0	0	0	No Ld.Fls. Reptd.
Arizona	6	2	2	9
Arkansas	7	2	5	12
California	20	2	11	28
Colorado	0	0	0	No Ld.Fls. Reptd.
Connecticut	8	1	2	10
Delaware	11	2	0	11
District of Col.	3	0	1	3
Florida	7	0	1	8
Georgia	1	0	0	1
Hawaii	6	0	4	10
Idaho	5	0	0	5
Illinois	5	0	2	7
Indiana	12	0	0	12
Iowa	46	0	5	51 (might be some overlap)
Kansas	0	0	0	0
Kentucky	9	0	0	9
Louisiana	1	0	0	1
Maine	0	0	0	No Ld.Fls. Reptd.
Maryland	16	2	4	20

(continued)

TABLE 7. (continued)

	No. Problems	Problem Adj.	Problems On	Total No. Sites Reporting
Massachusetts	7	1	3	11
Michigan	7	2	0	9
Minnesota	4	0	1	5
Mississippi	0	0	6	6
Missouri	2	0	0	2
Montana	3	0	2	3
Nebraska	1	0	0	1
Nevada	0	0	0	No Ld.Fls. Reptd.
New Hampshire	4	0	1	5
New Jersey	30	8	11	45
New Mexico	2	0	1	3
New York	27	3	15	41
North Carolina	12	0	1	13
North Dakota	5	0	0	5
Ohio	12	2	11	22
Oklahoma	5	0	2	5
Oregon	8	0	1	8
Pennsylvania	11	0	5	16
Puerto Rico	0	0	1	1
Rhode Island	2	3	2	7
South Carolina	13	1	1	15
South Dakota	0	0	0	0

(continued)

TABLE 7. (continued)

	No. Problems	Problem Adj.	Problems On	Total No. Sites Reporting
Tennessee	4	0	0	4
Texas	19	0	3	19
Utah	2	0	1	2
Vermont	2	0	0	2
Virginia	13	1	6	19
Washington	1	0	1	2
West Virginia	2	1	0	2
Wisconsin	6	0	1	6
Wyoming	0	0	0	No Ld.Fls. Reptd.
GRAND TOTAL	384	33	127	507

NOTE: Some landfills are listed in more than one category and examinations, we have compared the information received by mail and what was found in the field. This comparison indicates that one-third of the reports received by mail may have been inaccurate.

SITE SURVEY OF VEGETATION PROBLEMS ASSOCIATED WITH REFUSE LANDFILLS

Introduction

From the completed questionnaires received in response to the mail survey, landfill sites were selected which showed the best and the poorest vegetation growth associated with refuse landfills in the following nine climatic areas (Figure 1):

(1) Ar - Tropical wet.
(2) BS - Steppe or semi-arid.
(3) Bw - Desert or arid.
(4) Cf - Subtropical humid
(5) Cs - Subtropical dry summer.
(6) Dca - Temperate continental-warm summers.
(7) Dcb - Temperate continental-cool summers.
(8) Do - Temperate oceanic.
(9) H - Highland.

Procedures

Before planning the site visits, an inventory was made of all the equipment required for making the landfill vegetation and soil studies (Appendix D).

The following field procedure was designed to insure the maximum possible data from each landfill site visited. Field data were recorded on field inspection report forms (Appendices E and F).

1. After arriving at the site, preferably one involving the growth of trees and/or agricultural crops, with field equipment (Appendix D) communicate with the official contacts and make friends.

    a. Obtain a history of the site and the vegetation growth from the local officials. Find out what materials went into the landfill, how well they were compacted, how deep is the refuse, when it was put in the landfill; thickness and type of daily, intermediate and final cover, etc. Find out when vegetation was planted and how well it is growing.

    b. Record names, addresses, and telephone numbers of all contact persons. Record physical and mailing addresses of the site.

2. Make or obtain a rough map of the site noting areas of poor and good vegetation growth.

3. Establish reference points to and from which compass bearings can be taken and distance measurements can be made so that an accurate map can be made and the good and poor vegetation growth areas can be located accurately

in relation to the completed fill. This map should include the location of the completed landfill, vegetation, buildings, and where pictures were taken.

4. Take distance measurements and compass directions to reference points from the centers of the poor vegetation growth areas or from a specific location within the poor vegetation growth area.

5. When the poor vegetation growth areas are located, place or locate a reference marker in this area. Locate it at the center of the poor growth or at the spot previously located in number 4. All sampling points in the poor vegetation growth area should be taken in relation to the reference marker.

6. Repeat number 4 and number 5 for a comparable good vegetation growth area where the same species of crop is being grown as in the poor growth area.

7. Starting at the reference marker and moving out in as many directions as possible, take combustible gas readings at the 3' depth in the poor and good vegetation growth areas. The spacing and number of the sampling points will be determined by the size of the poor growth area and the amount of time available.

8. At intermediate sampling points in both areas take combustible gas samples at 1', 2', and 3' depths. Sample for O_2 and CO_2 at the 1' depth. Where possible, intermediate sampling sites should be located in the vicinity of sampling sites that were previously found to contain high concentrations of combustible gas at the 3' depth.

9. Take soil samples according to soil sampling procedure (Appendix G).

10. Identify species of the good and poor growth vegetation and the possible causes of poor growth.

11. Photograph the site including good and bad vegetation sampling locations. Record locations of photographs. Include vistas and close-ups of individual plants and/or leaves showing injury.

12. Sample and analyze any visible leachate which is in a vegetation growing area. Follow leachate sampling and analysis procedures (Appendix H).

13. Give contact people a general oral presentation of your observations and test results. If they request it, send them a copy of the report at a later date.

14. Record the following temperatures and their locations.

    a. On landfill

        1. Soil at 3' depth in area of poor vegetation growth and a high concentration of landfill decomposition gases.

        2. Soil at 3' depth in area of good vegetation growth.

b. Off landfill

1. At 3' depth in an area not influenced by landfill.

2. Soil at 3' depth in area of poor vegetation growth.

c. Ambient air in the shade.

15. Determine depth of cover over landfill refuse in areas of poor and good vegetation cover.

16. Note: Report data on "Landfill Vegetation Field Inspection Form" (Appendix E) and "Gas Sample Analysis Form" (Appendix F).

Evaluation of Landfills Surveyed

Introduction

During 1975, 1976, and 1977 over fifty landfills and former landfills were visited throughout the United States and Puerto Rico (Figure 2) for the purpose of evaluating the quality of vegetation growth on or adjacent to the former landfill.

The sites visited were chosen from the replies received from the mail survey supplemented by information obtained via telephone conversations. A half-dozen additional "landfills" were visited, but for various reasons they are not included in this report - in some cases they turned out not to be true refuse landfills and sometimes we were not able to obtain enough information to present reliable data.

The reports on the field trips are grouped by major climatic zones. These are arranged in alphabetical order according to their letter symbols. The detailed data are contained in Appendix I.

Landfills Surveyed According to Meteorological Regions

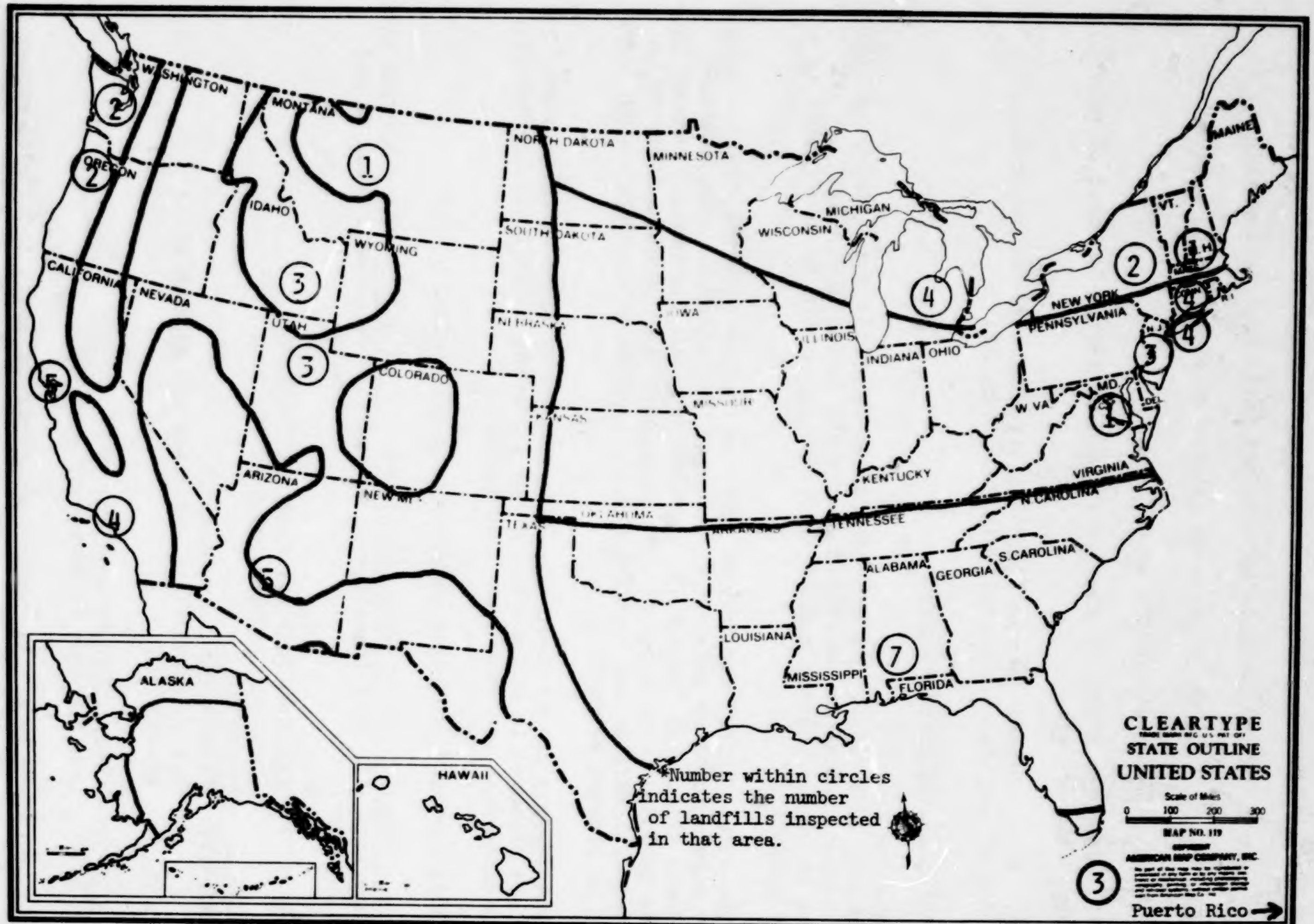
Ar - Tropical wet climate (Puerto Rico, 3/21-24/77)--The following three sanitary landfills were investigated in Puerto Rico between March 21 and March 24, 1977:

3/22/77 - San Juan Sanitary Landfill
Route #1, 7 miles south of San Juan.

3/23/77 - Bayamon Sanitary Landfill
Barrio Buena Vista, 4½ miles SSE Bayamon along
Route #167.

3/23/77 - Cayey Sanitary Landfill
3 miles east of Cayey off Route #1.

All of these landfills receive municipal and light industrial refuse. Bayamon was closed in 1974 by a court order whereas San Juan and Cayey are still operating. No attempts to vegetate any of these landfills was under-


WASHINGTON
OREGON
CALIFORNIA
NEVADA
IDAHO
MONTANA
WYOMING
UTAH
ARIZONA
COLORADO
NEW MEX
NORTH DAKOTA
SOUTH DAKOTA
NEBRASKA
KANSAS
OKLAHOMA
TEXAS
MINNESOTA
IOWA
MISSOURI
ARKANSAS
LOUISIANA
WISCONSIN
MICHIGAN
ILLINOIS
INDIANA
OHIO
KENTUCKY
TENNESSEE
MISSISSIPPI
ALABAMA
GEORGIA
FLORIDA
S.CAROLINA
N.CAROLINA
VIRGINIA
W VA
MD.
DEL.
N.J.
PENNSYLVANIA
NEW YORK
VT.
MAINE
ALASKA
HAWAII
2
2
5
4
1
3
3
5
4
7
2
4
3
1
4
CLEARTYPE
STATE OUTLINE
UNITED STATES
Scale of Miles
0 100 200 300
MAP NO. 119
AMERICAN MAP COMPANY, INC.
3
Puerto Rico

*Number within circles indicates the number of landfills inspected in that area.

Figure 2. Location of landfills evaluated for quality of vegetation growth*

taken; however, volunteer plants were scattered about the surface of San Juan and Bayamon.

On the San Juan landfill combustible gas was found to be higher in the areas where vegetation died than in areas which supported healthy vegetation. The root zone beneath a severely defoliated legume tree adjacent to Bayamon landfill contained higher combustible gas concentrations than a nearby healthy tree. No vegetation was growing on the Cayey landfill, and there were no signs of lateral gas migration.

In summary, combustible gas concentrations in the soil atmospheres related positively to dead and unhealthy vegetation.

BS - Steppe or semiarid climate (Utah and Montana, 8/30-9/3/76)--Four former landfills were examined in northern Utah and western Montana:

8/30/76 - Pioneer-Cannon Stakes Dairy, Salt Lake City, UT.

8/31/76 - Timpanogos Golf Course, Provo, UT.

8/31/76 - South Street Sanitary Landfill, Provo, UT.

9/03/76 - Great Falls Sanitary Landfill, Great Falls, MT.

All of these sites were planted with vegetation. However, only a minor part of Timpanogos Golf Course was constructed over a former landfill, and the Russian olive trees planted at the South Street Sanitary Landfill were actually adjacent to the former landfill. Correlations between high combustible gas and poor vegetation quality were noted at Great Falls and to a lesser extent at Pioneer-Cannon Stakes Dairy. The row of olive trees at the South Street Sanitary Landfill were planted on a berm, adjacent to the landfill, to which no combustible gas had migrated.

BW - Desert or arid climate (Phoenix-Glendale, Arizona, 1/17-1/20/77)--Five former landfills were examined in the Phoenix and Glendale region of Arizona:

1/18/77 - Del-Rio Sanitary Landfill, 7th St., Phoenix (A)

1/18/77 - Deer Valley Park, 19th Ave., Phoenix (B)

1/19/77 - Johnson's Farm, Olive Avenue & 98th Avenue, Maricopa Co. (C)

1/19/77 - Glendale Nursing Home, Olive and 107th Avenues, Maricopa Co. (D)

1/20/77 - Sutton's Farm, Northern Ave. and 103rd Ave., Maricopa Co. (E)

Combustible gas concentrations were generally low in the soil covering the refuse of these five landfills. No relation between combustible gas concentrations and vegetation quality were found at sites A, B and D and a very small negative relation (the more gas the poorer the vegetation) were found at sites C and E. The major problems with growing vegetation on these five sites appear to be a combination of rocky soil, lack of water, surface settlement, and transplanting difficulties.

Soil temperatures did not appear to be correlated with the viability of vegetation on any of the sites.

Cf - Subtropical humid climate (Southern Alabama, 8/15-24/76)--Seven former landfills were examined in the southern portion of Alabama:

8/16/76 - Montgomery #2 Wareferry Road, East Montgomery.

8/17/76 - Selma Sanitary Landfill, Route 80, Selma.

8/17/76 - Montgomery #1 Sanitary Landfill, Montgomery.

8/18/76 - Gautier St. Landfill, Tuskegee.

8/19/76 - Old Dothan City Landfill, Ashford.

8/20/76 - Atmore Sanitary Landfill, Escambia County.

8/23/76 - Chatom City Landfill, Chatom.

A correlation was found between dead or poorer quality vegetation and presence of combustible gases in the soil sites at Montgomery #1, Gautier St., Old Dothan City, and Atmore. Little combustible gas was found at Montgomery #2 and Selma sites and no combustible gas was found at the Chatom City landfill.

Cs - Subtropical dry climate (San Francisco-Los Angeles, California, 1/76)--In the San Francisco area five sites, all of which were reclaimed from San Francisco Bay by diking, were selected for investigation. The refuse ranged in depth from 15 to 40 feet, and in age from recent to over 80 years. The cover material on these sites tended to be very heavy clay, but it was frequently used very sparingly. As of January 1976, three of these sites (Marine Park, Galbraith, and Alameda) have been converted into golf courses; the remaining two (Mountain View and Oakland Scavenger) will become golf courses when filling is completed. All three golf courses have been developed successfully, but only the Marine Park site has not experienced serious problems with vegetation.

The three golf courses are located on refuse which contains a limited amount of putrescible material. The two landfills still to be converted into golf courses are said to contain much more putrescible refuse. This could result in more extensive problems with settlement and landfill gases than experienced at the other sites. A positive relationship was found between high concentrations of landfill gases and poor growth of cypress and Monterey pine trees at the Oakland Scavenger Company's Davis Street Landfill.

Four former landfills, all constructed by the County of Los Angeles Sanitary District, were examined in the Los Angeles area. They were the South Coast Botanic Garden, South Coast County Park, Mountain Gate Golf Course, and Mission Canyons #1, 2, and 3. All of these landfills have a maximum depth of at least 100 feet. A mixture of municipal and industrial waste was deposited at the South Coast Botanic Garden and South Coast County Park sites which are located in former diatomaceous earth mines. The remaining landfills, which were constructed in canyons, contain primarily municipal refuse. The Los Angeles landfills had considerably more cover material than those in the San Francisco area.

A considerable effort has been put into replanting these landfills by governmental agencies and private concerns. The results were the most successful we observed on our tour of sites throughout the country. All of the sites have had problems due to settlement, landfill gases or high soil temperatures. These problems, however, didn't appear to seriously detract from the overall success of the sites.

At the South Coast Botanical Garden a direct relationship was observed between the poor growth of vegetation and the occurrence of landfill gases in the soil. There was also found a direct relationship between the occurrence of high soil temperatures and poor growth of vegetation. A direct relationship between the occurrence of landfill gases in the soil and the poor growth of vegetation was also observed at the South Coast County Park, Mission Canyon Landfill, and the Mountain Gate Golf Course.

Dca - Temperate continental-warm summer climate (Northeast United States) --During 1975 and 1976 the following 12 landfills were visited in the warm summer temperate continental climatic region:

6/19/75 - Hunter Farm, Cinnaminson, NJ.

6/24/75 - DeEugenio Bros. Peachtree Farm, Glassboro, NJ.

7/31/75 - University of Connecticut at Storrs, Storrs, CT.

8/01/75 - Farmington Sanitary Landfill, Unionville, CT.

8/06/75 - Holyoke Sanitary Landfill #1, Holyoke, MA.

8/06/75 - Holyoke Sanitary Landfill #2, Holyoke, MA.

4/08/76 - Erlton Park, Cherry Hill, NJ.

6/29/76 - Kenilworth Demonstration Landfill Project, Washington, DC.

10/14/76 - Holtsville Sanitary Landfill, Brookhaven, L.I., NY.

10/14/76 - Kings Park Sanitary Landfill, Smithtown, L.I., NY.

10/15/76 - Huntington Sanitary Landfill, Huntington, L.I., NY.

10/15/76 - Bethpage Sanitary Landfill, Oyster Bay, L.I., NY.

Eight sites (Hunter Farm, DeEugenio Bros., Farmington, Holyoke #2, Holtsville, Kings Park, Huntington, and Bethpage) have dead trees and/or poor growing vegetation directly associated with the presence of landfill gases in the soil. However, the concentration of landfill gases at Farmington was very low.

At two sites, Kenilworth and Storrs, combustible gas correlated with poor growing vegetation in some instances; however, not all poorly growing vegetation was associated with the presence of combustible gas.

It appeared that poor planting practices and the lack of irrigation were the major contributors to the demise of trees planted on the former landfills at Kenilworth and Erlton Park.

Holyoke #1 was used as landfill for incinerator ash. No combustible gas was detected on or adjacent to this landfill.

Seven of these landfills (Hunter Farm, DeEugenio Bros., Holyoke #2, Holtsville, Kings Park, Huntington, and Bethpage) exhibited the correlation of landfill gases in the soil atmospheres and vegetation death in areas adjacent to the landfill. All seven landfills had been placed in former sand and gravel pits.

Dcb - Temperate continental-cool summer climate (Northeast United States, 8/75)--The following seven landfills were inspected during August, 1975:

8/7/75 - Roussel Park, Nashua, NH.

8/11/75- Guilderland Landfill, Guilderland, NY.

8/12/75- City of Auburn Sanitary Landfill, Auburn, NY.

8/18/75- Southeastern Oakland Incinerator Authority, Oakland Co., MI.

8/19/75- Cereal City Landfill #1, Battle Creek, MI.

8/20/75- Cereal City Landfill #2, Battle Creek, MI.

8/21/75- Kalamazoo Landfill, Oshtemo Twsh, MI.

There appeared to be no definite relation between vegetation injury and landfill gases at the Roussel Park or Kalamazoo Landfills. However, an excellent positive relationship was noted between high concentrations of landfill gases in the soil atmosphere and dead or dying vegetation at the Guilderland, Auburn, Oakland and Cereal City landfills. At the Oakland and Cereal City landfills the major vegetation death problems were associated with landfill gases migrating from the landfill beneath the ground. The following vegetation was apparently injured or killed by landfill gases:

Guilderland - volunteer aspen, sumac, and weeds

Auburn - willow trees

Oakland - lombardy poplar and black oak trees, weeds and grass

Cereal City #1 - red pine trees, weeds and grass

Cereal City #2 - white spruce, douglas fir, white fir, and shagbark hickory trees

Do - Temperate oceanic climate (Washington and Oregon, 6-7/76)--Two former landfills were examined in Seattle, Washington: East Campus of the University of Washington and Genesee Street Park. In Oregon two former landfills were evaluated: Day Island in Eugene, and Fowler's Farm in West Salem.

An excellent direct relationship was found between dead vegetation and/or barren ground and the presence of combustible gases in the soil atmosphere and anaerobic soil conditions at the two Seattle sites and at Day Island. The death of trees adjacent to Day Island was correlated positively with the underground migration of landfill gases from the landfill. High soil temperatures were also found to be associated with landfill gases at Day Island.

The wheat field at Fowler's Farm was growing over a former demolition landfill which produced only traces of combustible gas. Where the soil had not settled the wheat growing over the demolition material appeared to grow as well as that growing on nearby virgin ground.

H - Highlands climate (Idaho Falls, Idaho, 8/30-9/6/76)--The three former landfills which were visited in the Highlands climate region were:

9/2/76 - Fremont Park.

9/2/76 - Red Baron alfalfa field.

9/3/76 - Idaho Falls Child Development Center.

A good positive relationship was found between high combustible gas and poor quality vegetation at the Red Baron alfalfa field site, but at the other two sites very little landfill gas was found in the vegetation root zones. Therefore, no direct relationship was observed between the poor vegetation growth and the occurrence of landfill gas pollution in the soil atmosphere at these two sites.

Effects of Landfill Gases on Soil Quality

Top and subsoil samples from each of the nine climatic regions were analyzed for content of major and trace nutrients, pH, moisture, organic matter, conductivity and for soil texture. Data for landfills within each region were averaged (Appendix J, Tables 1-9) and analyzed statistically by Student's "t" test, where data were sufficient. Table J-10 contains a summary of all the topsoil data expressed as percent change (+ or -) in each constituent as the soil proceeded from a non-gas to a plus-gas condition.

The initial content of nutrient elements, as well as the pH of soils, in different landfills and among climatic areas varied widely. However, there was little difference in content of major nutrient elements (magnesium, phosphorus, potassium, and calcium) between gassed and ungassed soil. Since these elements are normally present in soil in hundreds or thousands of pounds per acre, a small percentage fluctuation in content would have a negligible effect on plant growth.

Nitrogen compounds (NO_3-N and NH_4-N) and trace elements (iron, manganese, zinc, copper, and boron) which are normally present in much lesser quantity, increased many fold in soil with high concentrations of gas in their atmospheres. In particular, the ratio of iron to manganese, a critical value in soil fertility, was frequently above the recommended range for adequate plant growth.

Conductivity which is a measure of total ion activity was, understandably, increased as well.

Soil pH was either increased or decreased, depending on the original condition of the soil; the pH of highly alkaline soils, such as those in Utah (steppe) and Idaho (highlands), decreased, while the more acid soils of the Northeast and Northwest increased in pH value.

Comparison Between Field Observations and Mail Survey Reports of Landfill Vegetation Conditions

Approximately 60 refuse landfills were visited during the 1975-77 field survey of landfill vegetation conditions. Thirty-seven of these had been reported through the mail survey prior to the field inspection. A comparison of what was reported by mail and what was found in the field indicated that about 23 (62%) of the responses were correct and about 14 (38%) were inaccurate.

The apparent conflict between what was reported by mail and what was found in the field for more than one-third of the reports was possibly due, in part, to errors in interpretation of the information supplied and to having many of the mail survey questionnaires completed by people who had not personally examined the landfill sites to determine the condition of the vegetation.

Table 8 presents the vegetative growth information reported by mail and the field observations from the same sites. The apparent accuracy of the mail survey report is given for each site. It was sometimes difficult to evaluate the accuracy of the mail report as simply either good or poor, since in a number of cases field examination indicated that part of the report was found to be correct and part incorrect.

TABLE 8. COMPARISON BETWEEN FIELD OBSERVATIONS OF LANDFILL VEGETATION CONDITIONS AND REPLIES TO THE MAIL SURVEY OF VEGETATION CONDITIONS

Climate *	Site	Reported by Mail	Observed in Field	Accuracy of Mail Statement
Ar	San Juan Landfill San Juan, Puerto Rico	Problems on the landfill	Problems on landfill	Good
Bsh-Bw	Deer Valley Park Maricopa County Arizona	Problems on landfill	Grass doing poorly Cause not known	Good
Bsh-Bw	7th Street Landfill Phoenix, Arizona	Problems adjacent to landfill	Dead trees near adjacent homes observed	Good
Bsh-Bw	103rd Ave. Landfill Maricopa County Arizona	No problems	Had been farmland Farming was abandoned due to settlement and gas	Poor
Bsh-Bw	Olive Ave. Landfill Maricopa County Arizona	No problems grass on landfill	Landfill converted to a nursing home, grass and trees doing well	Good
Bsk	Great Falls S.L.F. Great Falls, Montana	No problems on landfill	Wheat crop on landfill failed	Poor
Bsk	Pioneer-Cannon Stakes Dairy Salt Lake City, Utah	No problems with grass, trees and shrubs	Vegetation doing very poorly on this site	Poor
Cf	Montgomery City Landfill Montgomery, Alabama	No problems growing grass, trees and shrubs	Nothing planted only volunteer vegetation on site, mostly weeds	Poor

(continued)

TABLE 8. (continued)

Climate *	Site	Reported by Mail	Observed in Field	Accuracy of Mail Statement
Cf	Tuskegee Landfill Tuskegee, Alabama	No problems growing grass, trees and shrubs	Nothing growing on landfill at all	Poor
Cf	Dallas Co. Landfill Selma, Alabama	No problems growing grass, trees, or shrubs	Trees and volunteer vegetation doing very well	Good
Cf	Escanbia Co. Landfill Alabama	No problems growing trees	Trees (Pines) doing well, many were chlorotic, some erosion	Good
Cf	Old Dothan City Landfill Dothan, Alabama	No problems, grass and trees on landfill	Nothing observed planted on landfill, some trees adjacent declining gas suspected	Poor
Cf	Chatom City Landfill Chatom, Alabama	No problems growing trees on landfill	Trees doing well (seedlings)	Good
Cs	South Coast Botanical Gardens, Palos Verdes Los Angeles, California	No problems with grass, trees, and shrubs, problems adjacent	Good sucess on landfill But some problem areas were observed	Poor
Cs	Mission Canyon Los Angeles, California	Problems on landfill	Grass doing well, severe settlement problems observed	Good

(continued)

TABLE 8. (continued)

Climate *	Site	Reported by Mail	Observed in Field	Accuracy of Statement
Cs	Galbraith Golf Course Oakland, California	No problems with grass, trees, or shrubs	Problems observed due to thin cover, settlement, and gas	Poor
Cs	Alameda Municipal Golf Course Almadea,California	Problems on landfill	Severe settlement problems observed	Good
Dca	Oxon Cove Landfill Delaware	Grass growing on landfill	Wild vegetation, no planted vegetation	Poor
Dca	TVA, Land Between the Lakes Park Landfill Kentucky	No problems growing grass on landfill	Grass growing on landfill, some erosion problems	Good
Dca	Univ. of Connecticut Experimental Plot Storrs, Connecticut	Problems on landfill	Grass and alfalfa was growing noticably poorer over refuse	Good
Dca	Farmington City Landfill Unionville,Connecticut	Problems adjacent to landfill	Poor growth of volunteer species was observed on landfill, no evidence of problems adjacent	Poor
Dca	Overpeck Creek Hackensack, New Jersey	Problems on landfill	Some problems were observed but in all a successful operation	Good
Dca	Princeton Disposal S.L.F. South Brunswick, New Jersey	Problems adjacent	Leachate, indicating adjacent wood lot, landfill disrupting surface drainage, flooding trees	Good

(continued)

TABLE 8. (continued)

Climate *	Site	Reported by Mail	Observed in Field	Accuracy of Statement
Dca	Earle Landfill Naval Ammunition Depot Colts Neck, New Jersey	No problems growing grass, trees and shrubs	Pines planted-doing well Good cover of wild vegetation	Good
Dca	Cinniminson S.L.F. Cinniminson, New Jersey	Problems with vegetation adjacent to landfill	Corn, sweet potatoes killed on adjacent farm	Good
Dca	Kenilworth Landfill Washington, DC	No problems with grass and shrubs on landfill Some problems with trees	Grass doing well over most of site, many trees transplanted to site were dead	Good
Dca	Holtsville S.L.F. Brookhaven Long Island, New York	Problems on landfill Grass growing on landfill	Trees and grass not doing very well on landfill. Trees killed adjacent to landfill	Good
Dca	City of Madison S.L.F. Madison, Wisconsin	1) No problems with grass on landfill 2) Problems with grass on landfill	Grass generally doing well on landfill but areas did exist which wouldn't support grass	Good
Dca	Jackson City S.L.F. Jackson, Ohio	No problems with grass, shrubs and trees on landfill	Landfill largely unvegetated	Poor
Dcb	South-East Oakland Incinerator Co. S.L.F. Detroit, Michigan	Problems adjacent to landfill	Poplar trees and wild sumac killed adjacent to landfill	Good
Dcb	Cereal City S.L.F. Battle Creek, Michigan	Problems adjacent to landfill	Trees killed on two sides of landfill	Good

(continued)

TABLE 8. (continued)

Climate *	Site	Reported by Mail	Observed in Field	Accuracy of Statement
Dcb	Holyoke, S.L.F. Holyoke, Massachusetts	Problems with vegetation on landfill	Not much vegetation on landfill. Some dead trees observed	Good
Dcb	City of Auburn S.L.F. Auburn, New York	No problems with grass and shrubs on landfill Some problems with trees	Grass and trees doing well over most of the site. Some trees were having problems on the site	Good
Dcb	Guilderland S.L.F. Guilderland, New York	No problems with vegetation on landfill	Nothing was planted on landfill. Volunteer vegetation having problems	Poor
Do	Day Island Landfill Eugene, Oregon	Good grass growth, Some trees dead	Mostly good grass growth but some dead spots. Number of dead trees on and adjacent to completed landfill	Good
Do	Union Bay Univ. of Washington Seattle, Washington	Good grass cover	Numerous poor or no growth areas associated with high concentrations of landfill gas	Poor
H	City of Idaho Falls S.L.F. Idaho Falls, Idaho	No problems growing grass on landfill	Grass growing well on landfill. Some problems with trees observed on landfill	Poor

(continued)

TABLE 8. (continued)

*CLIMATES	
Abbreviation	Description
Ar	Tropical wet
Bsh	Steppe semiarid, hot
Bsh-Bw	Steppe semiarid-arid, hot
Bsk	Steppe semiarid cold
Bw	Desert or arid
Cf	Subtropical humid
Cs	Subtropical dry summer
Dca	Temperate continental warm summer
Dcb	Temperate continental cool summer
Do	Temperate oceanic
H	Highland

SECTION VI

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APPENDIX A

MAIL SURVEY INQUIRY LETTER

RUTGERS

COOPERATIVE
EXTENSION SERVICE
COOK COLLEGE

P.O. BOX 231, NEW BRUNSWICK, N.J. 08903

Telephone (201) 932-9443

The Cooperative Extension Service in cooperation with the Department of Plant Biology of Cook College, Rutgers University, New Brunswick, New Jersey is undertaking a survey to determine the extent of problems associated with growing vegetation adjacent to and on top of completed solid waste refuse landfills. Here in New Jersey we have observed a number of cases where trees and other vegetation adjacent to landfills have been killed by the lateral migration of landfill gases. We have also experienced many problems in growing adequate ground cover, particularly the deeper rooted vegetation, on the soil covering completed landfills. We would like to know if you know of any similar problems.

We also expect to conduct field and laboratory studies to help determine the cause of these vegetation growth problems and how they may be surmounted. Your assistance in helping solve these problems by returning the enclosed questionnaire in the self-addressed postage paid envelope will be greatly appreciated. If you would like to receive a report on the results of this study, please check the item next to your name and address.

Very truly yours,

Franklin B. Flower
Extension Specialist in
Environmental Sciences

bc
Enc.

COOPERATING AGENCIES: RUTGERS – THE STATE UNIVERSITY, U.S. DEPARTMENT OF AGRICULTURE, AND COUNTY BOARDS OF CHOSEN FREEHOLDERS. EDUCATIONAL PROGRAMS ARE OFFERED WITHOUT REGARD TO RACE, COLOR, OR NATIONAL ORIGIN. THE COOPERATIVE EXTENSION SERVICE IS AN EQUAL OPPORTUNITY EMPLOYER

APPENDIX B

OMB No. 158S 75005
Approval Expires 6/76

QUESTIONNAIRE: TO DETERMINE THE EXTENT OF VEGETATION GROWTH PROBLEMS ASSOCIATED WITH SOLID WASTE REFUSE LANDFILLS

Do you know of completed refuse landfills where there have been problems in growing vegetation on their cover material? Yes_____ No______

If yes, please list those landfills that have had the greatest problems.

NAME ADDRESS

1. ____
2. ____
3. ____
4. ____
5. ____

Do you know of refuse landfills where there have been problems of growing vegetation adjacent to the landfill? Yes______ No_______

If yes, please list the landfills that have had the greatest problems.

NAME ADDRESS

1. ____
2. ____
3. ____
4. ____
5. ____

(continued)

APPENDIX B. (continued)

Do you know of completed refuse landfills that have been able to grow a good vegetative ground cover with few problems? Yes______ No______

If yes, please list those completed landfills that are growing good vegetative covers and the type of cover they are growing.

NAME AND ADDRESS	TYPE OF COVER Grass	Shrubs	Trees	Other
1.				
2.				
3.				
4.				
5.				

If you have any comments on the effects of buried solid waste on living surface vegetation we would certainly appreciate hearing them. We would also appreciate your adding your name and address to this sheet and returning it to Frank Flower, Cook College, Rutgers University, New Brunswick, New Jersey 08903 in the enclosed self-addressed postage paid mailing envelope.

Name______________________________

Title______________________________

Address______________________________

____

____

_____Please send me a summary of the results of this refuse landfill - vegetation study when completed.

APPENDIX C

CLASSIFICATION OF MAIL SURVEY SOURCES

ORGANIZATION	1975 Date Sent	Number Sent	Form Letter No.
1. State Soil Conservation Service Offices	5/19	57	1
2. County Agents and Selected Specialists in New Jersey	5/19	60	2
3. State Cooperative Extension Service Directors.	5/20	63	3
4. EPA-SWMP Regional Representatives	5/29	10	4
5. State Solid Waste Management Agencies	5/30	58	5
6. Publications	6/2	33	6
7. S.W. Planning Course Registration, 6/13-15/72	6/2	15	7
8. APWA Educ. Fdn. Ref. Col. and Disposal Workshop, 5/9-10/72 Reg.	6/2	19	7
9. Sanitary Landfill Design Seminar, 6/28-29/73 Reg.	6/5	55	7
10. New Jersey Conservation Districts	6/6	15	7
11. Major Solid Waste Management Firms	6/6	10	7
12. Engineering Foundation SLF Conf. 8/13-18/72 Reg.	6/12	81	7
13. Other	6/5-12/31	130*	7
14. Gas and Leachate from Landfill Conf. 3/25-26/75 Reg.	7/18	191	7
15. Solid Waste Processing Div., ASME Membership	7/20	194	7
16. New York State Soil Conservation Districts	9/25	12	7
	TOTAL	1,003	

* - Approximate number

APPENDIX D

LIST OF FIELD EQUIPMENT

1- compass
2- pen and note pads
3- 6' and 50' steel tapes
4- string
5- camera and film
6- vegetation I D books
7- roller tape
8- pail
9- clip board
10- felt marking pens
11- close up lenses for camera
12- hammer and mallet
13- screwdrivers
14- wrenches - adjustable and pipe
15- pliers - standard, long nose, water pump
16- garden trowel
17- tool boxes
18- masking tape
19- electrician's knife
20- plastic bags for soil samples
21- shovel
22- soil profile extractor
23- 3" soil auger
24- first aid kit
25- bags to carry equipment and supplies
26- gloves
27- insect repellent
28- boots
29- thermos
30- soil sampling procedure - SOP
31- gas sampling procedure - SOP
32- water sampling and testing procedures - SOP
33- files for reports
34- preaddressed mailers
35- refill for 3' bar hole maker
36- Explosimeter with extra catalyst and 10/1 dilution tube
37- O_2 analyzer
38- 20% CO_2. analyzer
39- 60% CO_2 analyzer
40- 3' thermometer
41- extra tips for bar hole maker
42- water analysis kit
43- 3' gas sampling probe
44- paper clips and rubber bands
45- rubber stoppers
46- O_2 and CO_2 refills
47- O_2 and CO_2 analyzer repair kits
48- Explosimeter calibration kit
49- 3' and 4' bar hole makers

APPENDIX E

LANDFILL-VEGETATION FIELD INSPECTION FORM

SITE: DATE:
    Name
    Address

    Phone

CONTACTS:
    Names
    Addresses

    Phones

LANDFILL:
    Size
    Cover (Quantity and Quality)
        Daily
        Intermediate
        Final
    Refuse
        Type
        Depth
    Degree of Compaction

TEMPERATURES: (°F. and Location)
    Ground (3 ft. depth)
        Over Landfill - Good Growth -
                        Poor Growth -
        Virgin Land -
    Ambient (in shade) -
Settlement
Leachate
Odor
Age
    Started
    Completed
Cell Size
Current Use
Ultimate Use

(continued)

APPENDIX E. (continued)

Vegetation (Quantity and Quality) on Landfill
- Grass
- Shrubs
- Trees
- Other

Vegetation (Quantity and Quality) Adjacent to Landfill
- Grass
- Shrubs
- Trees
- Other

General Notes and Observations: (Include an outline map of area.)

APPENDIX F

FIELD GAS SAMPLE ANALYSIS FORM

*Soil Sample Taken

	COMBUSTIBLE GAS AT											
	1'			2'			3'			1'	1'	
SITE	LL	10/1	20/1	LL	10/1	20/1	LL	10/1	20/1	% O_2	% CO_2	REMARKS

APPENDIX G

FIELD SOIL SAMPLING PROCEDURE

a. Select and map site.
b. Locate sampling stations in areas of good and poor vegetation growth.
c. Take samples from three or four points within sampling stations to reduce the chance of taking samples from an unindigenous area.
d. Avoid surface contamination such as fertilizer or garbage. To avoid contamination when taking samples do so quickly and firmly. Without rotating the sampling tube insert the tube directly into the soil. A bucket can be used to transfer the soil from the sampler to the bag. Use 3" soil auger or garden trowel to obtain sample when sampling tube cannot be used.
e. Obtain a pint of both surface soil (topsoil)and subsoil for analysis. Fill two sampling bags. Take the surface soil sample first.
f. Measure the depth of the topsoil. If the topsoil is less than 8" deep take the surface soil sample from the first 8" of soil; if the topsoil is more than 8" deep take the surface soil sample from the total depth of the topsoil.
g. Take the subsoil sample from the next 8" of soil depth using the same hole(s) from which the topsoil sample was obtained.
h. At the time of sampling, characterize the soil as to whether it is wet, moist, or dry, by squeezing it. Water will drip from wet soil when squeezed, moist soil will remain as a ball, while dry soil will crumble after being squeezed.
i. When putting the sample in the bags for transport to the soils laboratory be sure to seal them tightly to prevent water loss.

APPENDIX H

FIELD LEACHATE SAMPLING AND ANALYSIS PROCEDURE--

The following method for sampling leachate was established.

1. Secure a sample of the leachate in a glass or polyethylene bottle (100-200 cc).
2. If the solution is very dark, it may require dilution with distilled water before applying the color tests.
3. Test for the following components by methods described in the Hach Water Testing kit. Be sure to rinse the vials with distilled water after each test.
    a. pH
    b. Free and total acidity
    c. Alkalinity
    d. Copper content
    e. Iron content
    f. Chloride content
4. Determine total conductivity by means of the Beckman Mho-Gun.

APPENDIX I

DETAILED OBSERVATIONS AND FIELD DATA FROM LANDFILL SITE SURVEY

AR-TROPICAL WET CLIMATE

San Juan Sanitary Landfill, Puerto Rico

In 1967 the San Juan Landfill, located seven miles south of the city of San Juan on Route #1, began accepting incinerated municipal refuse and light industrial refuse. In 1972, after the incinerator was closed, sanitary landfill operations began. The 100-acre landfill now accepts approximately 1700 tons/day of municipal and light industrial refuse which has reached a depth of eighty feet in some places.

The daily cover spread at the end of each day's landfilling ranged from zero to six inches during the period of time this site has been operated as a sanitary landfill. In areas where landfilling has been completed, the final cover ranged from six inches to twelve inches. Much of the refuse has been placed in a low lying marshy area, presumably above the water table. However, according to Charles Romney (Natural Resource Specialist, 1550 Ponce Leon Boulevard, San Juan, Puerto Rico) the majority of the refuse was dumped into the water lying in the marsh.

The completed portions of this landfill have not been planted with vegetation and are currently not being used by anyone. Volunteer vegetation has established itself in some areas where the final cover is the deepest. However, much of the area is devoid of vegetation. A continually burning landfill fire on the north side of the landfill was responsible for the death of a group of adjacent trees when the fire flared up and began burning the leaves on the trees.

One volunteer legume tree growing near the edge of the same face has died this year. Combustible gas at three feet beneath this tree was about seven percent. Twenty feet away and still on the edge of the refuse, was a living legume tree with no combustible gas in the root zone down to three feet. Soil samples were taken to better ascertain the cause of death.

Approximately 500 feet southeast of these legume trees was a group of cucurbit (cucumberlike) plants. In the area of good growth, no combustible gas was found at one foot, trace amounts were found at two feet, and ten percent at three feet. The gas at three feet probably has little if any effect on the growth and survival because of the shallow root system. In a generally barren area twenty feet away, combustible gas was found in trace amounts at one foot, and at two feet reached forty percent of the soil gas atmosphere.

In summary, combustible gas related positively to dead vegetation and bare cover soil.

Bayamon Sanitary Landfill, Puerto Rico

In 1970, the municipality of Bayamon began operating a sanitary landfill for the disposal of municipal solid waste. The landfill is located at Barrio Buena Vista, about four and a half miles south-southeast of Bayamon along Highway #167. Operations in the landfill were begun in 1970 and discontinued in 1974 by order of the United States District Court in San Juan, Puerto Rico, as a result of a lawsuit by residents of the area.

Prior to the closure of the landfill, and at the request of the United States District Court, the United States Geological Survey conducted a field test and collected and analyzed samples of the leachate flowing from the landfill (June and July 1972). The results of these analyses is reported in the proceedings Gas and Leachate from Landfills: Formation, Collection and Treatment, (EPA-600/9-76-004), United States Environmental Protection Agency, Cincinnati, Ohio.

The landfill covers approximately ten acres. No vegetation was planted on the landfill; however, thick grass covered most of the site and a few small volunteer trees and shrubs are scattered about the site. The combustible gas concentrations could not be determined beneath any of the trees or shrubs on the landfill because the ground contained too many rocks.

Adjacent to the landfill, on the south slope, were two large trees. One of these had lost all of its leaves during the previous year and another, forty feet away, was healthy. High combustible gas concentrations were found in the root zone of the dead tree but no combustible gas was found beneath the living tree. O_2 and CO_2 readings were similar beneath both trees and the soil temperatures averaged about 90°F.

Leachate was streaming from the bottom of the south slope of the landfill and running over the soil around a group of large trees growing adjacent to the refuse. Many of these trees have died, particularly the large ones in the area where the leachate is running.

In summary, no trees were planted on the landfill; however, volunteer grasses and shrubs have completely covered the area, but the cover was too rocky to obtain soil gas readings. Adjacent to the landfill, combustible gas was found beneath a dead tree and no combustible gas was found beneath a living tree. A number of trees adjacent to the landfill have also apparently been killed by excessive leachate.

Cayey Sanitary Landfill, Puerto Rico

This forty to fifty acre operating landfill, located three miles east of Cayey off Route #1, receives approximately six tons of municipal and light industrial refuse every day from a few surrounding communities. Operation began in 1971 by filling a canyon. By March, 1977 it was up to eighty feet deep in the center. Daily cover is scraped off of an adjacent ridge on the north end of the area and placed over the refuse at the end of each day's operations. Approximately six inches to one foot of daily cover is used. No leachate or settlement was apparent.

No attempts have ever been made to vegetate this landfill. In addition, no volunteer plants occupied any part of this site. However, adjacent to the south side of the landfill is a sugar cane field which has been abandoned for reasons other than the landfill's impact. No migrating combustible gas was found in this field but the refuse has been adjacent to the field for only three months.

When the Cayey Sanitary Landfill is completed it is planned that tennis and basketball courts will be built and various trees and shrubs will be planted.

BS-STEPPE OR SEMIARID CLIMATE

Pioneer-Cannon Stakes Dairy, Salt Lake City, Utah

This former 150+ acre landfill was reported to be currently used as pasture land. Examination of the site revealed that the area is located in lowlands near the Great Salt Lake, where the salt water table is close to the surface. Municipal refuse had been deposited in this area with the hopes that it would raise the level of the soil above the water table so that the salt could be leached out of the soil.

Two fields were examined. The field completed in 1975 was planted in 1976 with alfalfa and sudan grass. Neither crop was observed growing at the time of our inspection. Instead only weeds were observed growing in this field. The second field had been completed as a landfill in 1966. This was the third year that a crop was planted on it. There was noticeably better growth in this field than in the first field.

Carbon dioxide and combustible gas concentrations were much higher and oxygen much lower in the poor vegetation growth field than in the better (second) field (Table I-1). Although the second field showed generally good growth there were large patches in the field where nothing was growing. Combustible gas readings were the same in the no-growth areas of this field as in the areas where the vegetation was doing very well. It is suspected that high salt concentrations may be responsible for these no growth areas.

Settlement was noticeable in both fields. The farmer who cultivates these fields reported that this settlement hinders the operation of the farm equipment. The settlement also leaves depressions that cause ponding. This is a problem because the ponded water collects salt from the subsoil which remains on the surface after the water evaporates.

TABLE I-1. PERCENT COMPOSITION* OF SOIL GASES IN FIELDS WITH GOOD AND POOR VEGETATIVE GROWTH

PIONEER-CANNON STAKES DAIRY, SALT LAKE CITY, UTAH

	Good Alfalfa Growth		Weeds Only	
Sample Depth	2'	3'	2'	3'
O_2	-	17	-	10
CO_2	-	<0.5	-	22
Combustible Gas	5	-	46	-

*Average of 2 to 11 readings

Timpanogos Golf Course, Provo, Utah

The Timpanogos Golf Course is located on South Street, east of Interstate 15, between East Street and University Avenue in Provo, Utah. Nine holes of the Golf Course were reported to be built over a former refuse landfill. When combustible gas checks were made in this area toward the south end of the course, it was apparent that no refuse had been placed in this area, since no combustible gas was detected. We were then informed by the golf course superintendent that only a small area between the tenth and fourteenth fareways had been filled with municipal refuse. This small area, which was filled in 1946, measures approximately 200 feet long and 35 feet wide with a maximum depth of six feet. Combustible gas reading at one spot was about thirteen percent of the soil gas atmosphere at the two foot depth. Here considerable settlement had resulted in very noticeable undulations of the ground surface. The grass in this and all other areas where refuse was placed was growing just as well as on that part of the golf course where there was no refuse. No combustible gas was recorded at one foot anywhere in the settled area. The irrigation of the grass probably promoted a shallow root system. This may explain the good grass growth despite the presence of combustible gas at the two foot depth in one location. The roots are probably growing above the combustible gas.

South Street Sanitary Landfill, Provo, Utah

This 100-acre landfill was completed in 1973 with the placement of municipal refuse in depths of ten to fifteen feet. One side of the landfill adjoins a major highway (Interstate 15). Russian olive trees were planted along this side of the landfill. Although these trees were reported to have been planted on the landfill, it was found that they had been planted on a soil dyke surrounding the landfill. The trees were in good condition and ranged in height from nine to twenty feet. No combustible gas was found along the 1,000 foot length of this tree planting. The soil appeared to be of a better quality where the trees were growing than that on the landfill where very little vegetation grew. At one point on the landfill the combustible gas concentration was found to be greater than fifty percent at the one and a half foot depth.

At this landfill the soil dyke apparently prevented the gases of anaerobic decomposition from migrating horizonatally out of the landfill.

Great Falls Sanitary Landfill, Great Falls, Montana

The 25+ acre Great Falls Sanitary Landfill began operation in 1963 with the acceptance of municipal refuse and some agricultural wastes. This continued until around 1973 when shredded refuse was also accepted. Shredded refuse was placed over that part of the landfill now occupied by a wheat field. Six inches of daily soil cover was placed over the non-shredded refuse, but no soil cover was spread over the shredded refuse until the end of the filling operations in 1975 when twelve to eighteen inches of final cover was spread.

In the fall of 1975, following the completion of the site, part of the former landfill was seeded with winter wheat as was an adjacent field on virgin land. According to the owner, the wheat germinated normally in the fall of 1975 and survived the winter as did the wheat planted on virgin land. However, with the onset of the summer dry period the wheat on the landfill began to show signs of chlorosis and remained stunted. Dieback was extensive. The total wheat yield from the landfill area was about one-half that normally expected from a field this size. It was reported that the wheat in certain areas of the refuse-filled area did not grow taller than three to four inches.

Combustible gas and CO_2 readings in these severely growth-stunted areas were higher and O_2 concentrations lower than in the areas of better growth (Table I-2). A very good correlation exists between the presence of combustible gas and stunting and dieback of the wheat plants.

TABLE I-2. PERCENT COMPOSITION OF SOIL GASES IN WHEAT FIELDS WITH GROWTH OF DIFFERENT QUALITIES

GREAT FALLS SANITARY LANDFILL, GREAT FALLS, MONTANA

	Excellent Growth*		Good Growth**		Poor Growth**	
Sample Depth	1'	3'	1'	3'	1'	3'
O_2	-	-	-	16	-	12
CO_2	-	-	-	12	-	21
Combustible Gas	0	-	0	-	12	-

*Off landfill
**On landfill

BW-DESERT OR ARID CLIMATE

Del-Rio Sanitary Landfill, Phoenix, Arizona

The thirty-five foot deep Del-Rio Sanitary Landfill, which covers 1/3 square mile, is presently operated by the city of Phoenix, Arizona. Some sections of the landfill have been completed. One of these areas adjacent to the scale house was planted with a number of cottonwood trees in 1974. Most of our investigative work was done here.

The landfill began operations in 1969 using a cell size of approximately 300'/64'/8' and accepting only municipal refuse. A caterpillar type bulldozer was used both to compact the refuse and spread the six inches of daily cover as well as the thirty inches of final cover. Because of the geologic history of the Phoenix area, the cover material contained many round rocks. Consequently, the soil in which the cottonwood trees were planted had to be imported from another area.

Five of the six cottonwood trees planted adjacent to the scale house were planted in 3' 6" inside diameter, 6' long cement drain pipes. These vertically set pipes extended two feet above the surface of the cover material. The sixth tree was not growing in a cement pipe but was planted in the cover material.

No combustible gas was found at any depth in these containers except for a trace in one container at three feet (Table I-3). Combustible gas averaged 1-2 percent at two feet beneath the tree not planted in the container. This tree appeared to be the most healthy of the six trees. Four of the five containers supported grass growth while no grass was growing in the fifth container. The cottonwood in this container has died and was the third tree of three which had been planted and died in that container. The poplars in the four other containers did not appear completely healthy, but they had grown this year and next year's buds appeared normal.

There appeared to be no correlation between combustible gas concentration and the health of the poplar trees. Although some combustible gas was present in the root zone of the mostly healthy poplar, it did not appear to effect the viability or growth of the tree.

TABLE I-3. PERCENT COMPOSITION* OF SOIL GASES AT DEAD AND LIVING POPLARS

DEL-RIO SANITARY LANDFILL, PHOENIX, ARIZONA

	Living Poplar		Dead Poplar	
Sample Depth	2'	3'	2'	3'
O_2	-	21	-	21
CO_2	-	2	-	1
Combustible Gas	1-2	-	0	-

*1-2 readings

Deer Valley Park, Phoenix, Arizona

Six acres of this landfill have been vegetated in anticipation of developing the site into a municipal golf course. There is six to eighteen feet of municipal refuse in the landfill with cover thickness ranging from about thirty inches to ten feet.

Bermuda grass was planted over the entire area and was observed to have difficulty growing on the site. There were many patches over the site where the grass wasn't growing. No correlation was found between these patches and the occurrence of landfill gases in the soil (Table I-4). There was also no visible difference in the growth of the grass between the area where the cover was thirty inches thick and where it was ten feet thick.

TABLE I-4. PERCENT COMPOSITION* OF SOIL GASES IN FIELDS WITH GOOD AND POOR GRASS GROWTH

DEER VALLEY PARK, PHOENIX, ARIZONA

	Good Growth		Poor Growth	
Sample Depth	1'	2'	1'	2'
O_2	20	-	20	-
CO_2	4	-	4	-
Combustible Gas	-	9	-	0.5

*1-2 readings

Adjacent to the landfill there was observed a number of dead and dying trees which had been transplanted to the site. Three of these trees were examined and combustible gas. About 2% was found at a three foot depth near only one of them.

It appears that the problems with the vegetation on and adjacent to this landfill are caused by something other than landfill gases, such as lack of water or poor soil conditions.

Johnson's Farm, Maricopa County, Arizona

This former sanitary landfill of 9.1 acres was completed in December 1970 after being operated for a year and four months. The landfill contains an average of nine feet of municipal refuse with thirty inches or less of cover material.

The site had been planted with barley for three to four years. The farmer reports that the yield from this area was one-fourth of the yield from adjacent virgin land. The plants were only half as high in this area, the roots were stunted and there was poorer germination in the field over the refuse. Settlement was also reported to be severe enough to hinder the operation of farm equipment and disrupt surface drainage.

At the time that this data was collected the field over the refuse was fallow. The farmer had given up in his attempts to farm the site. The soil appeared to be of noticeably poorer quality in the field over the refuse than the adjacent virgin land. There were barren patches among the weeds and barley that grew on the site. In these areas where nothing was growing combustible gas concentrations were found to range from four to five percent at a depth of one foot, and from fifteen to thirty percent at the three foot depth. In areas on the refuse where the vegetation was doing fairly well no combustible gas was found at the one to two foot depth. No combustible gas was found in the active farm field adjacent to the former landfill farm field (Table I-5). The farmer reported that the barley planted in the field off the landfill had grown much better than the barley on the landfill.

There does appear to be a positive relationship between the poorest barley growth and the presence of landfill gases.

TABLE I-5. PERCENT COMPOSITION* OF SOIL GASES IN BARLEY FIELDS WITH GOOD AND POOR GROWTH

JOHNSON FARM, MARICOPA COUNTY, ARIZONA

	Good Growth**		Fair-Poor Growth***		Very Poor Growth***	
Sample Depth	1'	3'	1'	2'	1'	3'
O_2	20	-	21	-	18	-
CO_2	0	-	0	-	5	-
Combustible Gas	0	0	0	0	5	23

*Average of 2 readings
**Off landfill
***On landfill

Glendale Nursing Home, Maricopa County, Arizona

The Glendale Nursing Home was built in 1975 on the site of a former sanitary landfill. The refuse was removed from the area where the building was located and replaced with clean fill and crushed rubble. However, the refuse remained beneath the area where landscaping plants were planted.

Landfilling with municipal refuse began on this site in 1966 and was completed in 1974 to a depth of approximately fifteen feet. Six inches of daily cover were spread at the end of each day's filling and about thirty inches of final cover was placed at the completion of the landfilling operations.

In the summer of 1976 the area surrounding the building was planted with grass and various tree species, including olive, orange, and palm trees. Silver dollar trees were planted in December 1976. Settlement areas in the lawn and in one of the parking lots accumulate water when the irrigation system is turned on. Despite frequent irrigation, approximately one-quarter of the trees planted were dead or showed signs of stress as of January 19, 1977.

No combustible gas was found beneath any of the trees on the site except for one trace reading at three feet under one living palm tree. However, carbon dioxide concentrations reached 9 percent and 4.5 percent beneath two dead silver dollar trees while no carbon dioxide was found beneath a living silver dollar. However, this situation was reversed beneath two olive trees where the highest CO_2 (8%) was found under a living olive tree and the lowest concentration (2%) beneath a dead olive tree (Table I-6).

TABLE I-6. PERCENT COMPOSITION* OF SOIL GASES BENEATH LIVING AND DEAD TREES

GLENDALE NURSING HOME, MARICOPA COUNTY, ARIZONA

	Living Trees		Dead Trees	
	Silver Dollar	Olive	Silver Dollar	Olive
Sample Depth	27"	36"	15"	36"
O_2	20.5	12	15	21
CO_2	0	8	7	2
Combustible Gas	0	0	0	0

*Average of 1-2 readings

No consistent relationship were found between vegetation survival and presence of combustible gas or carbon dioxide. The dead plants appear to have succumbed because of transplanting difficulties.

Cal Sutton's Farm, Maricopa County, Arizona

Since this thirty-eight acre sanitary landfill was completed in 1972 wheat, cotton, and barley have been grown on this site in alternate years with the aid of regular irrigation.

Municipal refuse was deposited in this area from December, 1970 to April, 1972 to a total depth of fourteen feet. Six inches of daily cover was spread over the refuse at the completion of each day's operation, and two to three feet of cover material was spread as a final cover.

The yield from this landfill field is as much as forty percent below that obtained from an adjacent field on virgin land. The soil on the former landfill field dried quicker, requiring more frequent irrigation, than the adjacent virgin field. Settlement has caused many undulations throughout the field forcing the farmer to fill in the settled areas with soil from unsettled areas of the field thereby creating a non-uniform soil depth throughout the field. Many of these settled areas supported little vegetation.

Combustible gas readings were taken in two good growth areas and two poor growth areas on the former landfill field. Most of the test points could not be penetrated beyond one foot because the soil contained many large rocks; however, three points were penetrated to three feet. The soil became considerably softer and easier to penetrate at two feet indicating that perhaps the refuse began at this depth.

Very low combustible gas concentrations (averaging about two percent) were recorded at one foot in a poor barley growth area, and no combustible gas was found in the good growth areas. However, at three feet, the combustible gas concentration was about fifteen percent beneath the good growth area.

Barley growth on the former landfill was poor although very little combustible gas was found on the former landfill. Low combustible gas readings were found in the bad growth areas while the good growth areas contained almost no combustible gas in the topsoil (Table I-7). The extremely rocky hard soil over the former landfill probably contributed to the poor growth.

TABLE I-7. PERCENT COMPOSITION* OF SOIL GASES IN VARIOUS BARLEY GROWTH QUALITY AREAS

CAL SUTTON'S FARM, MARICOPA COUNTY, ARIZONA

	Adjacent to Former Landfill	On Former Landfill	
	Best Growth	Good Growth	Poor Growth
Sample Depth	3'	1'	1'
O_2	20	20	21
CO_2	0	1	0
Combustible Gas	0	trace	2.0

*Average of 1-2 readings

CF-SUBTROPICAL HUMID CLIMATE

Montgomery #2 Wareferry Road, East Montgomery, Alabama

This operating landfill was located in a former sand and gravel pit covering about thirty acres. It contains general municipal refuse to a depth of about twenty-five feet in most places. Adjacent to the landfill is a fifty-acre soybean field. The refuse nearest to the soybean field is about five years old.

The field was examined for possible landfill gas damage. The soybean plants on the edge of a dirt road separating the landfill from the soybeans were severely stunted, averaging about six inches high. Plants further in the field averaged three feet in height. This stunted area was approximately twenty feet wide and followed the edge of the road for the entire length of the field. The farmer felt that this stunting was caused by the farm equipment compacting the soil when it turned at the end of the field.

Combustible gas checks in these stunted areas revealed that a small amount of landfill gas was present. At a one-foot depth combustible gas comprised an average of one percent, no CO_2 was found and O_2 comprised twenty-one percent of the soil atmosphere. At a depth of three feet combustible gas averaged five percent of the soil atmosphere. A very slight odor was present one foot beneath the stunted plants.

The root systems of the stunted plants were compared with those from the normal growth area. The roots of the stunted plants extended three to four inches into the soil while those in the normal area reached down one foot.

Three other stunted areas within the main field up to 109 feet from the refuse were checked for combustible gas. No combustible gas was found in any of these areas. The stunting in these areas was probably due to ponding.

Another stunted area located along the edge of the field was examined. No combustible gas was found in this area. The lack of landfill gases in this area and the low concentrations of combustible gas where it was found and the lack of CO_2 where the combustible gas was found supports the farmer's opinion that the stunting was due to soil compaction.

Selma Sanitary Landfill, Route 80, Selma, Alabama

This small (three acre) landfill contains eight to ten feet of municipal and light industrial refuse. The refuse was only covered occasionally, resulting in an open-dump operation most of the time. This site was used from 1969 to 1973. Upon completion of landfilling the refuse was covered with two to three feet of soil and was planted with loblolly pine seedlings. When planted in 1973 these seedlings ranged from eighteen inches to over seven feet in height.

Very little combustible gas was present in the soil over the refuse. Of twenty-two test points only two contained combustible gas at a depth of one foot. The highest reading at a depth of two feet was about five percent, beneath a loblolly pine which was seventy-five inches high, one of the largest trees on the site. Since loblolly pine has a characteristically shallow lateral root system, two feet of soil should contain most of the roots. Although the tree heights ranged from eighteen inches to over seven feet, no correlations were found to exist between tree height and the presence of combustible gas. In general, the trees were doing as well as might be expected in similar soil not located over a former refuse landfill.

Montgomery #1 Sanitary Landfill, Montgomery, Alabama

This operating landfill was begun in the early 1960's. The refuse ranges from ten feet to fifteen feet deep over an area of approximately twenty acres. The daily cover ranges from zero to six inches, with a final cover of about two feet. However, some areas lacked adequate cover and the refuse remained exposed. Some areas on the landfill have remained flooded for long periods of time preventing any vegetation from growing. Settlement appeared to have caused the depressions in which the water accumulated.

Trees and shrubs covered the fifteen-year old portion of the landfill while shrubs, small trees and annual weeds have become established on the ten year old portion. No combustible gas (or occasionally very low combustible gas) concentrations were recorded in these vegetated areas. A positive correlation was found between high combustible gas concentrations and death of a Kentucky coffee tree, while low combustible gas was found beneath a living coffee tree (Table I-8).

TABLE I-8. PERCENT COMPOSITION* OF SOIL GASES BENEATH LIVING AND DEAD KENTUCKY COFFEE TREE

MONTGOMERY #1 SANITARY LANDFILL, MONTGOMERY, ALABAMA

	Living Tree		Dead Tree	
Sample Depth	1'	2'	1'	2'
O_2	21	-	20	-
CO_2	0	-	$\frac{1}{2}$	-
Combustible Gas	-	1	-	$12\frac{1}{2}$

*Average of 1-3 readings

Gautier Street Landfill, Tuskegee, Alabama

This three acre landfill operated from 1955 to 1970. The landfill contains municipal refuse ranging in depth from a few feet to about twenty feet. There are two to three feet of final cover.

Native forest vegetation is adjacent to the landfill on three sides. Volunteer vegetation from this forest was found growing on the site, particularly mimosa and loblolly pine. No attempts had been made to replant this landfill.

Two loblolly pine trees were checked for combustible gas in their root zones; one healthy tree, and one which exhibited severe dieback. Combustible gas readings were similar beneath these two trees. However, CO_2 was much higher under the unhealthy tree (Table I-9).

Four mimosa trees were compared; two were experiencing severe dieback, two were healthy. Combustible gas was higher on the average near the symptomatic trees. CO_2 was found to be higher near the unhealthy trees (Table I-9).

TABLE I-9. PERCENT COMPOSITION* OF SOIL GASES BENEATH HEALTHY AND UNHEALTHY TREES

GAUTIER STREET LANDFILL, TUSKEGEE, ALABAMA

	Healthy Trees				Unhealthy Trees			
	Loblolly Pine		Mimosa		Loblolly Pine		Mimosa	
Sample Depth	2'	3'	2'	3'	2'	3'	2'	3'
O_2	-	20½	-	18½	-	19	-	20
CO_2	-	0	-	2½	-	18	-	0
Combustible Gas	10	-	3½	-	4½	-	17½	-

*Average of 1-5 readings

Old Dothan City Landfill, Ashford, Alabama

This seven year old landfill accepted municipal refuse from the city of Ashford from 1970 to 1974. The refuse was deposited in trenches dug approximately fifteen-feet deep, thirty-three feet wide and up to 400-feet long. There is about two feet of final cover over this refuse.

Weeds covered most of the site. No trees, either volunteer or planted, were found growing on the landfill. There were a few dozen twenty-five to thirty-five year old loblolly pine trees adjacent to the eastern edge of the landfill. Two of the trees had been dead for more than a year while most of the other trees were reasonably healthy. Many of the trees in this area had damage near the ground as would result from a fire years before.

The two dead trees were compared with two living trees (Table I-10). The combustible gas in the soil atmosphere near the dead trees at the one foot depth averaged 1½ percent and at the three foot depth 17½ percent. This was considerably higher than what was found near the healthy trees. Oxygen was found to be lower near the dead trees but more CO_2 was found near the living trees. The dead trees had evidence of cankering above the "fire damage". This might have been due to a disease. To what extent this could have contributed to the demise of the trees could not be determined. The data indicates that the trees could have been damaged by migrating landfill gases.

TABLE I-10. PERCENT COMPOSITION* OF SOIL GASES BENEATH LIVING AND DEAD LOBLOLLY PINE TREES

OLD DOTHAN CITY SANITARY LANDFILL, ASHFORD, ALABAMA

	Living Loblolly Pine Trees		Dead Loblolly Pine Trees	
Sample Depth	1'	3'	1'	3'
O_2	21	-	17	-
CO_2	5½	-	0	-
Combustible Gas	0	1	1½	17½

*Average of 1-8 readings from root zones of 2 dead and 2 live trees

Atmore Sanitary Landfill, Escambia County, Alabama

Landfilling began at this five-acre site in August, 1973 and continued until August, 1976. It accepts general municipal refuse and wood, which is burned. The refuse was placed in trenches about fifteen-feet deep and forty-feet wide and 300-feet to 400-feet long. It was covered daily with six inches of sandy soil. The final cover over the trenches is two feet deep. When completed the site is to be reclaimed as forest land.

The first trench was completed in February 1974 and was planted with fifteen-inch tall loblolly pine seedlings in March 1974. Over 1,000 trees were planted in rows six inches apart. Approximately twenty percent of these trees were dead or missing in August 1976. The living trees ranged from seventeen inches to over seven feet tall. These pines were judged to be doing fairly well compared with similar plantings on virgin soil by the local Soil Conservationist who is involved in reforestation projects throughout this county.

The soil atmospheres were compared between where the trees had grown very well, being seventy-seven inches to ninety-seven inches tall, and where the trees weren't growing well, being seventeen inches to thirty inches tall. Very little CO_2 was found anywhere on this landfill and O_2 concentrations were found to be about normal at a one foot depth near both groups of trees. Combustible gas concentrations were generally low at the one foot depth near all of the trees, but it was slightly higher near the poorly growing trees. At a three foot depth there was much more combustible gas near the poorly growing trees (Table I-11).

This data indicates that landfill gases may be hindering the growth of some of the trees, but not enough to noticeably reduce the overall success of the site.

TABLE I-11. PERCENT COMPOSITION* OF SOIL GASES BENEATH TALL AND SHORT LOBLOLLY PINE TREES

ATMORE SANITARY LANDFILL, ESCAMBIA COUNTY, ALABAMA

	77" to 97" Tall Loblolly Pines		17" to 30" Tall Loblolly Pines	
Sample Depth	1'	3'	1'	3'
O_2	21	-	21	-
CO_2	0	-	$\frac{1}{2}$	-
Combustible Gas	0	5	1	$11\frac{1}{2}$

*Average of 2-8 readings

Chatom City Landfill, Chatom, Alabama

The Chatom City landfill was begun in 1967 to enable household refuse to be brought here for open burning. The fill was completed in 1974 and was covered at that time with one to two feet of course,sandy soil. The entire site, including the adjacent cut over woodlot, which is used as a source of cover material, is five acres.

Slash pine trees were planted six feet apart over the entire site in 1974 in order to reclaim the land. The pines were planted as twelve inch seedlings. They were observed to range in height from twelve inches to forty-two inches in August, 1976.

No combustible gas was found in the soil anywhere on or adjacent to the landfill. In general, the trees planted over the area where the refuse had been open-burned were doing as well as the trees planted adjacent to the refuse. Apparently, landfill gas was not a problem here because the organics had been removed from the refuse by combustion prior to the final closing of the landfill in 1974.

CS-SUBTROPICAL DRY CLIMATE

City of Alameda Golf Course, Alameda, California

This eighteen-hole golf course was constructed on a completed refuse fill in 1955. Filling operations began sometime in the 1870's and ceased in 1953. The composition of the refuse is variable over the site, some areas having clean fill. About twenty feet of fill has been placed over bay muck.

Although in general the trees are growing well over the golf course, (eucalyptus are up to thirty feet tall), there are localized severe problems with vegetation growth and surface settlement. In one case, a 15 x 20-foot bare spot on a fairway contained combustible gas at the one-foot depth of greater than fifty percent. Adjacent to this spot are a number of Monterey pine trees which exhibited a good deal of variability in growth although all were planted in 1957. Almost no combustible gas was found in the root zone of these trees. The only combustible gas reading of any magnitude was $4\frac{1}{2}$ percent at a three-foot depth. The soil around these trees was not uniform. In some places it was extremely hard.

Poor drainage appears to be the greatest problem. Surface drainage is poor, particularly where extensive settlement has occurred. The dikes keep out the salty bay water, but the fresh water doesn't have any outlet because of these dikes and the dense nature of the clay subsurface soil. This area was examined during a severe drought, yet fresh water was found to be saturating the soil in several places at a depth of only one foot.

Galbraith Golf Course, Oakland, California

This golf course was constructed in 1966 on a 180-acre landfill completed in 1965. The landfill contains trash, rubble, and industrial waste in depths of fifteen to thirty feet. The cover-material depth ranges from zero to one foot. Settlement problems have occurred in some areas of the course. There has also been a large loss of trees, particularly pines, over the entire site. Some of these trees have blown over due to lack of a deep root structure; others were known to be killed by industrial waste; the cause of death for some was unknown.

Mounds of soil were deposited on the cover material along the fairways to provide for the growth of some trees. Other trees were planted directly in the cover material without mounds. It was noted that most of the trees in the mounds were eucalyptus while most of the pines had been planted directly in the cover material.

The most extensive vegetation growth problems occur on and around the eighth fairway. In this area the grass was growing poorly and much settlement was evident. At several points in this area the combustible gas concentration in the soil atmosphere at a one-foot depth was five percent or greater. Some of the pine trees along the fairway were doing much better than others, but combustible gas readings around several of these healthy trees were not significantly different than those around the poorly growing trees. Combustible gas at one foot depth near these trees ranged from 0 percent to about $5\frac{1}{2}$ percent, and at the two-foot depth it ranged from 0 percent to greater than fifty percent.

Some of the mounds are located in areas containing combustible gas. Data were collected to determine the ability of the mounds to provide gas-free soil for root growth. Two mounds were examined. Both were about thirty inches high at the center and about twenty-five feet in diameter. The eucalyptus trees on both mounds appeared to be growing rather well. In the cover material next to the mounds, combustible gas was found in two of six points tested at a one foot depth. At a two-foot depth these same six points all had combustible gas ranging from about five percent to greater than fifty percent. On one of the mounds combustible gas was absent down to a depth of two-feet six inches at three points. On the other mound no combustible gas was found at one and two-foot depths, but at a depth of three feet, concentrations were four percent to five percent.

The mounds were relatively free of gas to a depth of one foot; however, gas concentration was also very low in the cover soil. Therefore, the absence of appreciable gas in the root areas on the mounds may have been due to the cover soil serving as a barrier to the gas.

Oakland Scavenger Company, Davis Street Sanitary Landfill, San Leandro, California

This 247-acre landfill receives most of the municipal refuse generated in the Oakland-San Leandro area. The landfilling was begun around 1950, and is scheduled to be completed in 1977 or 1978. The twenty to forty feet deep landfill will then be converted into a golf course.

At the time of this inspection the only vegetation on the site was located along the bay front, which was landscaped in 1969 to reduce the eyesore created by the operating landfill. Four species of trees: Monterey pine, cypress, and two species of eucalyptus(red gum and blue gum) have been planted. A shrub, bottle brush, was also found here. At first this site was not irrigated and problems of poor tree growth were attributed to lack of water. After an irrigation system was installed, in early January 1976, many of the trees which were having growing problems showed improvement.

Two large eucalyptus did not improve and appeared to be dead. No refuse, or to be more accurate, no differential texture that would indicate refuse in this area was encountered in penetrating the soil at these eucalypti with a bar-hole maker. This, in conjunction with the lack of any combustible gas in the soil atmosphere, indicates that these eucalyptus trees were probably not on the landfill but on the dike which had been constructed to keep out bay water.

Some of the trees located on the refuse showed stress symptoms, most noticeably chlorosis (browning of the needles in pine) and stunting. Soil gas readings were taken near four Monterey pines, two of which were healthy and two unhealthy (Table I-12). Similar readings were taken for a healthy and an unhealthy cypress (Table I-12).

The data collected near the pine trees indicates a possible positive relationship between the occurrence of combustible gas and stress symptoms. The data collected near the cypress are inconclusive due to the very low concentrations of combustible gas.

TABLE I-12. PERCENT COMPOSITION* OF SOIL GASES BENEATH HEALTHY AND UNHEALTHY TREES

OAKLAND SCAVENGER COMPANY-DAVIS STREET SANITARY LANDFILL, SAN LEANDRO, CALIFORNIA

	Healthy Trees				Unhealthy Trees			
	Monterey Pine		Cypress		Monterey Pine		Cypress	
Sample Depth	1'	2'	1'	2'	1'	2'	1'	2'
O_2	$19\frac{1}{2}$	-	-	-	20	-	21	-
CO_2	$4\frac{1}{2}$	-	-	-	0	-	0	-
Combustible Gas	-	$5\frac{1}{2}$	-	0	-	$20\frac{1}{2}$	-	trace

*Average of 1-8 readings

Marine Park Golf Course, San Leandro, California

Nine holes of this eighteen hole golf course have been constructed on a completed landfill. The filling operations ceased in 1967 and the course was completed in 1972. Most of the refuse consisted of nonputrescible construction debris and paper deposited to a depth not exceeding twenty feet. Two to three feet of clay were put over the refuse as cover.

The golf course has not experienced problems with settlement or excessive loss of vegetation. A wide variety of trees and shrubs are growing over the site. Eucalyptus trees, many of which are over twenty feet tall, were the most noticable species. One area where several large pine trees had died was pointed out by the grounds-keepers. No combustible gas was found in this area. Mr. Frank Green, superintendent, attributed much of this loss to the roots growing into the refuse.

One area was reported to have some sewage sludge deposited in it. A variety of trees was growing in this area and appeared to be doing well, as was the grass. The only apparent interference with good grass growth was that caused by puddling in areas of poor drainage.

At a depth of two feet, throughout an area where healthy eucalypti were growing, combustible gas readings ranged from trace to over fifty percent at nine of the eleven sampling points. At a one-foot depth only two of these eleven points had any combustible gas (approximately two percent and five percent). These data indicate that the heavy clay cover-material was probably effective in containing the landfill gases.

Mountain View Sanitary Landfill, Mountain View, California

This operating landfill will be converted to a golf course when completed. The entire area has been reclaimed from San Francisco Bay by diking. The refuse ranges in depth from twenty-five feet to about forty feet and the cover material, while variable over the site, averages about two feet. A 1200#/cubic yard refuse density is said to be obtained in the landfill.

Three areas were examined. The first had a variety of eucalyptus species, planted by the University of California in about five feet of cover. These seemed to be doing well. Seven points were sampled in this area but only one contained combustible gas, and that was at a depth of three feet.

The second area examined had a row of eucalyptus trees which were planted on the most inland dike. Many of these trees were dead and most of those still living were experiencing severe dieback. The soil in this area was very hard and dry. Two of the dead trees were checked for combustible gas. None was found.

The third area examined was a 380' x 290' nursery of young trees which are to be transplanted when the golf course is landscaped. This area is on the refuse and the cover consists of one foot of compacted clay underlying two feet of loam, into which sewage sludge was incorporated. The trees are irrigated. These plantings are expected to help in the selection of tree species for planting on the golf course. The plot is laid out in a grid pattern containing twenty-five species and nineteen individuals of each species. The different species varied in their reaction to this situation, some being healthier than others. The redwood trees Sequoia gigantea and S. serpervirens had the greatest problem adjusting; all had died.

The feature of interest was not the ability of the different trees to grow here, but rather the ability of the clay layer to contain the landfill gas. Of thirty-two combustible gas readings taken at a one-foot depth, only five recorded the presence of combustible gas (ranging from a trace to about fifty percent). The four high readings were all obtained from within a forty-five foot long oblong area near the edge of the plot. Of fourteen combustible gas readings taken at two-foot depths, only two contained combustible gas, and that was only at trace concentrations. At a depth of three feet, all thirteeen points tested contained combustible gas. The readings ranged from a trace to greater than fifty percent.

South Coast Botanic Garden, Palos Verdes, California

The South Coast Botanic Garden is located on the Palos Verdes peninsula. It was constructed on an eighty-seven acre former landfill having a maximum depth of 165 feet. The landfill was constructed from 1957 to 1965 in a former diatomaceous-earth mine which had operated from 1929 to 1954. Diatomaceous earth was used as landfill cover.

The Botanic Garden, which was begun in 1961, is one of the first to be developed on a completed sanitary landfill. It boasts of 140 plant families, about 700 genera and over 2,000 species, with a total of more than 150,000 plants. The entire garden, with the exception of a concrete-lined pond was placed over a former municipal and industrial waste landfill.

The garden was observed to be well vegetated and presented a pleasing appearance. Problems establishing vegetation on the site were reported, these include wind toppling trees, settlement, and high soil temperatures. This survey confirmed the problems that were reported. Of particular interest was the occurrence of high soil temperatures which were apparently excluding the growth of vegetation in at least one area (Table I-13). Operators of the garden blamed many vegetation losses upon high soil temperatures but not on landfill gases. However, high concentrations of landfill gases were frequently found associated with high soil temperatures.

TABLE I-13. PERCENT COMPOSITION OF SOIL GASES AND SOIL TEMPERATURES AT HEALTHY AND DEAD OR POORLY GROWING VEGETATION

SOUTH COAST BOTANIC GARDEN, PALOS VERDES, CALIFORNIA

	Healthy Vegetation						Dead or Poorly Growing Vegetation					
	African Daisy			Hybrid Broom Cytisis racemosis			African Daisy			Hybrid Broom Cytisis racemosis		
Sample Depth	1'	13"	36"	1'	13"	36"	1'	13"	36"	1'	13"	36"
O_2	11	-	-	19½	-	-	14	-	-	11½	-	-
CO_2	16½	-	-	0	-	-	13½	-	-	15	-	-
Combustible Gas	2½	-	-	0	-	-	>15	-	-	22	-	-
Temperature °F	-	88	109	-	61	73	-	99	130	-	102	104

Note: Ambient air temperature = 50°F @ 8:45 am and 65°F @ 2:30 pm

In this survey of the Garden, combustible gas and elevated levels of carbon dioxide were found at a depth of one foot in several areas. An examination of the soil atmospheres near four living and two dead acacia trees revealed a possible correlation between the death of the trees and the presence of landfill gases in the soil atmosphere (Table I-14). There was also evidence of a canker disease on some of these trees both living and dead. To what extent this disease contributed to the demise of these trees could not be determined in these uncontrolled field conditions.

An area where grass was observed to be growing very poorly or not at all was compared with an area where the grass was doing very well. Combustible gas and carbon dioxide were found to be much higher in the soil where the grass wasn't growing well (Table I-14).

TABLE I-14. PERCENT COMPOSITION* OF SOIL GASES AND SOIL TEMPERATURES** AT HEALTHY AND UNHEALTHY VEGETATION

SOUTH COAST BOTANIC GARDEN, PALOS VERDES, CALIFORNIA

	Healthy				Unhealthy			
	Acacia Trees		Grass		Acacia Trees		Grass	
Sample Depth	1'	3'	1'	3'	1'	3'	1'	3'
O_2	18½	-	19½	-	13	-	17	-
CO_2	2	-	0	-	12	-	7	-
Combustible Gas	½	-	1½	-	19	-	11	-
Temperature °F	-	60	-	57	-	78	-	64

*Average of 4-11 readings
**Single readings

It appeared that much of the success of the vegetation growth was associated with the lack of landfill gases in the root zone. This may have been due to the diatomaceous earth cover-material acting as a gas barrier.

South Coast County Park, Palos Verdes, California

South Coast County Park is located across Crenshaw Boulevard from the South Coast Botanic Garden. It currently consists of a twenty-five acre former landfill tract which is being used as a park. Ultimately the park will cover 173 acres of former landfill, and it will include an eighteen hole golf course plus other recreational facilities. Some settlement has occurred and migration of combustible gas into an adjacent church building south of the landfill had to be corrected by venting through an induced draft system. This gas is burned in an outdoor flare.

Manhattan rye grass planted on the site appears green and luxuriant. Some planted trees are underlain with a layer of large gravel and vented with vertical 4 1/4 I.D. plastic pipe to a depth of two feet. The area is well irrigated, fertilized, and aerated. The soil temperatures fell between 50° to 57° F.

Landfill gas is extracted from this site by Reserve Synthetic Fuels, Inc., who produce pipeline quality methane for sale to the local gas company.

Data are presented in Table I-15 comparing two sets of planted trees. In both cases, high concentrations of combustible gas were found in the root zone of the poorly growing trees while very little was found in the root zones of the healthy trees.

TABLE I-15. PERCENT COMPOSITION* OF SOIL GASES AT HEALTHY AND UNHEALTHY VEGETATION

SOUTH COAST COUNTY PARK, PALOS VERDES, CALIFORNIA

	Healthy Vegetation				Dead or Chlorotic Vegetation			
	Melaleuca		Aleppo Pine		Melaleuca		Aleppo Pine	
Sample Depth	1'	3'	1'	3'	1'	3'	1'	3'
O_2	7	-	17	-	$3\frac{1}{2}$	-	11	-
CO_2	5	-	$\frac{1}{2}$	-	43	-	25	-
Combustible Gas	4	5	<1	>50	>50	>50	>50	>50

*Single readings

Mountain Gate Golf Course, Santa Monica, Los Angeles, California

Mountain Gate Golf Course is a privately owned eighteen-hole executive golf course which was built on the site of a landfill (Mission Canyon #4 and #5) which operated from 1965 to 1972. Plantings of Pinus halepensis (Aleppo pine), Eucalyptus, Myaporum, Acacia, Ficus and other species were established in 1973. Grass types consist of Penncross Bent on the greens, Seaside Bent on collars, and Bermuda grass on the fareways.

Extensive settling has been experienced on the golf course, amounting to as much as eleven feet in a single year. Daylight cracks are observable between landfill and non-landfill areas. The main irrigation lines are buried only in virgin ground. They are elevated above ground in the refuse deposition area. Flexible couplings and elevators permit movement within the piping system as settling occurs. Still there are about two breaks per week in the feeder lines as a result of uneven settlement of the underground pipes. The seven greens in the refuse deposition areas are underlain with four to five-inch thick concrete slabs, buried $2\frac{1}{2}$ to 3 feet in the ground. A four to five-inch-deep layer of one-inch stone overlays the concrete slabs. Still, high combustible gas readings were observed in the soils of the greens. It has been estimated by the golf course construction superintendent that costs of maintenance of a golf course on a landfill (including irrigation, repair of daylight cracks and piping, drainage, etc.) are twenty percent higher than on a conventional course.

The soil atmospheres in areas where the vegetation was growing well were compared with that in areas where the vegetation was growing poorly. Two two-needle pine trees were compared, one of which was dead and the other alive. The combustible gas in the soil near each of the trees was about the same but CO_2 was lower and O_2 was higher near the tree which was living (Table I-16). Where aleppo pines and Eucalyptus trees were growing poorly landfill gases were found in the soil atmosphere, and where these trees were growing well no landfill gases were found (Table I-16).

TABLE I-16. PERCENT COMPOSITION* OF SOIL GASES AT HEALTHY AND UNHEALTHY VEGETATION

MOUNTAIN GATE GOLF COURSE, SANTA MONICA, CALIFORNIA

	Healthy Vegetation		Dead or Poor Growth Vegetation	
	Two-Needle Pine	Aleppo Pine & Eucalyptus	Two-Needle Pine	Aleppo Pine & Eucalyptus
Sample Depth	1'	1'	1'	1'
O_2	14	20	9	9½
CO_2	7½	0	12½	5
Combustible Gas	5-15	0	5-15	>50

*Single readings

Mission Canyons #1, 2, and 3, Los Angeles, California

In June, 1960, the County Sanitation Districts of Los Angeles County commenced sanitary landfilling operations in Mission Canyons 1, 2, and 3, located in the Santa Monica mountains in northwestern Los Angeles (Figure I-1.). Operations continued until October, 1965 when they were shifted southerly to Mission Canyons 4 and 5 which were to become Mountain Gate Golf Course.

By January of 1976 a grass cover had been established on MC #1; MC #2 had been planted along its easterly side with a 50 to 100-foot wide landscaped buffer zone; and MC #3 had been developed into a park containing grass, shrubbery, and trees.

Deposition of refuse in MC #1 was completed in 1963. Three or more feet of cover was reported to have been placed over this ten acre area, which is now planted with mixed grasses including alfalfa. These grasses, which are irrigated regularly, appear to be healthy. However, there are continuing problems with extensive, uneven settlement and with "daylight

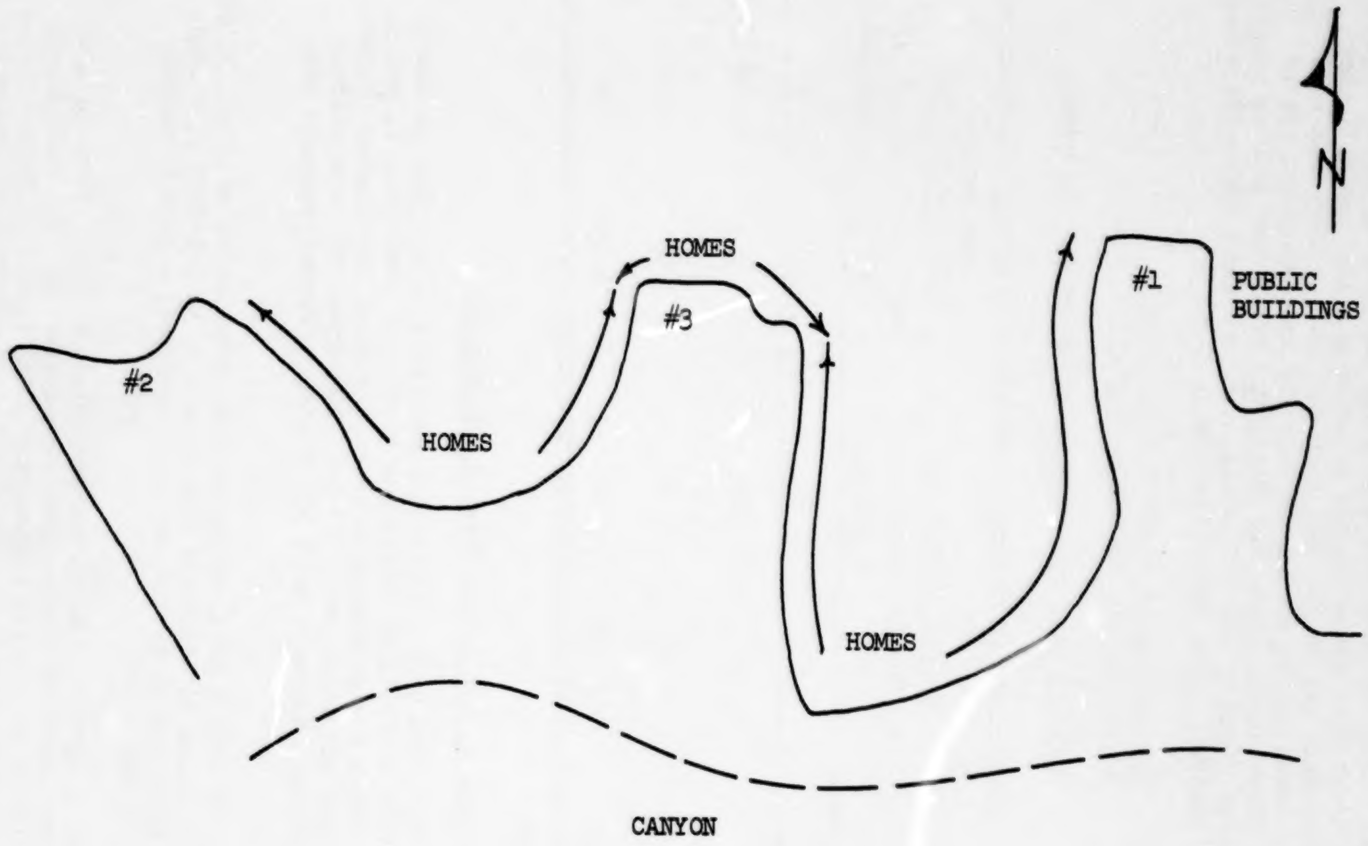
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Figure I-1. Mission Canyon Landfills 1, 2, and 3, North Sepulveda Blvd,. Los Angeles, California

cracks" along the interface of the refuse and virgin ground.

Mission Canyon #2 is a fifteen acre tract atop a landfill started in 1962 and completed in 1965. Currently one and-a-half acres along the eastern boundary have been developed toward its ultimate use as an aesthetic barrier between adjacent, developed residential areas and future landfill operations. Plantings of 1973, which are located primarily on a seven to eight-foot deep berm at the eastern edge of the refuse, appear to be growing well. This may be due, at least in part, to the presence of five operating gas-extraction wells on the tract. These wells were installed to prevent lateral gas migration. Two ground gas checks in the vicinity of the landscape barrier revealed only very minor amounts of combustible gas in the soil atmospheres.

Mission Canyon #3 is a ten-acre park built on a landfill that was constructed between 1960 and 1965. The refuse is reported to be as deep as 200 feet in places. Grass has been planted over the park along with scattered trees. The main plantings were Eucalyptus and Pinus plus a few Acacia.

The surface of this park was originally graded to promote drainage towards the periphery of the park. Since the original landscaping in 1973 settlement has reversed this grade so that at the present time most of the runoff is carried towards the center of the park. Here the refuse is deepest and settlement has been most extensive.

Table I-17 presents field data. In general, little combustible gas was found in the soil atmosphere until the three foot-depth was reached. This may have been due, at least in part, to the ten gas-extraction wells located around this site. Landfill gases were not found in the root zones of the vegetation. The gases collected are burned in a waste-gas burner located near the bottom of Mission Canyon. The trees and grass in general appeared to be growing fairly well. However, there were a number of bare spots in the lawn, a few of the trees were doing poorly, and a majority of the pines appeared chlorotic. In places the soil was water-logged at the time of our visit, apparently because of recent irrigation.

TABLE I-17. PERCENT COMPOSITION* OF SOIL GASES AT HEALTHY AND UNHEALTHY VEGETATION

MISSION CANYON #3, LOS ANGELES, CALIFORNIA

	Healthy Vegetation			Unhealthy Vegetation		
	Eucalyptus	Two-Needle Pine	Grass	Eucalyptus	Two-Needle Pine	Grass
Sample Depth	1'	1'	1'	1'	1'	1'
O_2	$20\frac{1}{2}$	21	21	$17\frac{1}{2}$	$20\frac{1}{2}$	21
CO_2	0	0	0	$1\frac{1}{2}$	2	0
Combustible Gas	0	0	0	0	$<\frac{1}{2}$	<1

*Average of 1-4 readings

Dca-TEMPERATE CONTINENTAL WARM SUMMER

Hunter Farm, Cinnaminson, New Jersey

The 100-acre landfill across the street from the Hunter Farm was reported to have been started in 1965 in an old sand-and gravel-pit. The fill material is 40-80 feet deep and consists of all types of refuse. The refuse was placed directly across the road from the farm beginning about 1969. Damage to farm crops was first noted in 1970.

At the time of this inspection, the farm field across the street to the southwest of the landfill was planted with corn. Approximately 250 feet away from the landfill was an irregularly shaped area of corn exhibiting severe stunting and chlorosis. The surrounding corn looked very healthy.

The dimensions of the chlorotic and stunted zone in the field were determined and soil atmosphere was checked for the presence of combustible gases, oxygen and carbon dioxide. Approximately thirty rows of the corn exhibited poor growth. A transect was made along which combustible gas, oxygen and CO_2 were measured at the one-foot and three-foot depths respectively, at fifteen foot intervals. The good growth areas contained no combustible gas while the area which exhibited chlorosis and stunting contained an average of fifteen percent combustible gas (Table I-18). The CO_2 concentration was much higher and the O_2 concentration considerably lower in the area of poor growth. Overall, we found positive relationship between the presence of decomposition gases and poor corn growth.

TABLE I-18. PERCENT COMPOSITION* OF SOIL GASES AT HEALTHY AND UNHEALTHY CORN

HUNTER FARM, CINNAMINSON, NEW JERSEY

	Good Corn Growth		Poor Corn Growth	
Sample Depth	1'	3'	1'	3'
O_2	13½	-	3½	-
CO_2	4½	-	20	-
Combustible Gas	-	0	-	15

*Average of 2 readings

DeEugenio Brothers Peachtree Farm, Glassboro, New Jersey

Landfilling at this site adjacent to the peach orchard began in February, 1968. The filled material included refuse collected from household collections plus some demolition material, industrial waste and sewage sludge. The landfill is located in a former sand-and gravel-pit which had a depth of about twenty feet. Upon completion of the landfill, the peach farmer had hoped to plant additional peach trees over the filled area by enlarging the adjacent orchard. However, in 1971, two years after the completion of the filling operations adjacent to the N-E side of the orchard, peach trees closest to the refuse filled area began to die. One year later soil gas measurements were made, and combustible gases and CO_2 were detected beneath many of the dead trees.

By June 1975, many additional trees had died. Soil gas checks in the area revealed that combustible gas was beneath a chlorotic, mostly defoliated mature peach tree, while no combustible gas was found beneath the adjacent mature peach tree which showed moderate growth (Table I-19).

New seedlings had been planted on the southeast side of the landfill and the trees in the row closest to the landfill had all died. Combustible gas was present beneath a dead tree in this first row, but it was not present beneath a living tree in the second row away from the refuse. The presence of combustible gas was found to be directly related to the death of peach trees in this orchard adjacent to the refuse landfill.

TABLE I-19. PERCENTAGE COMPOSITION* OF SOIL GASES VS PEACH TREE VIABILITY

DE EUGENIO PEACH ORCHARD, GLASSBORO, NEW JERSEY

	Good Growth Trees				Poor Growth or Dead Trees			
	Saplings		Mature		Saplings		Mature	
Sample Depth	1'	3'	1'	3'	1'	3'	1'	3'
O_2	19	-	20	-	19	-	16½	-
CO_2	0	-	0	-	0	-	5½	-
Combustible Gas	-	0	-	0	-	5	-	>15

*All readings are single samples

University of Connecticut, Storrs, Connecticut

The University of Connecticut began a project in 1970 to determine if corn could be grown over a completed landfill. One hundred and fifty foot long trenches thirty feet wide and about ten feet deep were spaced thirty feet apart and filled with mostly newspapers. A corn crop was subsequently planted over the trenches and intertrench areas. The project ran out of funds at this time. However, a decrease in corn yield was observed over the trenches as compared to the intertrench areas. The soil over the trench areas was also reported to be of poorer quality.

In 1975, alfalfa and clover were planted over this area. Our field observations of these crops showed a significant decrease in flower height over the trench areas (Table I-20). Some sample stations in the trench (poor growth) area contained combustible gas at three feet while other sample stations contained no combustible gas. No sample stations in the intertrench (good growth) areas contained combustible gas. Therefore, in some cases, the presence of combustible gas related directly to poor vegetation growth while in other cases there was no correlation between poor growth and the presence of combustible gas.

TABLE I-20. PERCENT COMPOSITION* OF SOIL GASES AT AREAS OF GOOD AND POOR GROWTH, ALFALFA AND VETCH

UNIVERSITY OF CONNECTICUT, STORRS, CONNECTICUT

	Good Growth	Poor Growth
Sample Depth	3'	3'
O_2	17½	20
CO_2	0	0
Combustible Gas	0	0-33

*Average of 1-9 readings

Farmington Sanitary Landfill, Unionville, Connecticut

This landfill contains an average of about twenty-five feet of municipal refuse covered with about two feet of soil. The landfill was completed in 1973.

The area examined had been planted with about 200 Scotch pine trees. Few of them were still living when this data was collected. Lack of care and competition from volunteer species, particularly quaking aspen, might account for their demise. A good deal of variation was noted in the condition and dispersal of the quaking aspens over the site. A negative relation was found between the presence of combustible gas and CO_2 and the condition and dispersal of aspens. Several patches of tall (5 to 8 feet) dense stands of aspens were observed. In other areas the aspens were under four feet tall and scattered, or they weren't growing at all. Where the quaking aspens were doing well no combustible gas was found at the one-foot depth and an average of ½ percent CO_2 and 19 percent O_2 was found in the soil atmosphere. Where the trees weren't growing, or were growing poorly, the soil atmosphere contained, on the average, about 1 percent combustible gas, 9 percent CO_2 and 14 percent O_2 at the one-foot depth (Table I-21).

This data is consistent with the possibility that the presence of landfill gases hindered the establishment of the aspens on this site.

TABLE I-21. PERCENT COMPOSITION* OF SOIL GASES AT AREAS OF HEALTHY AND POOR GROWING QUAKING ASPENS

FARMINGTON SANITARY LANDFILL, UNIONVILLE, CONNECTICUT

	Healthy Aspens	Poor Growing Aspens
Sample Depth	1'	1'
O_2	19	14
CO_2	$\frac{1}{2}$	9
Combustible Gas	0	1

*Average of 3 readings

Holyoke Sanitary Landfill #1, Holyoke, Massachusetts

This landfill was begun in 1960 and was still in operation when this data was collected. The refuse is about forty feet deep and consists almost entirely of incinerator ash.

No attempts had been made to establish vegetation on the site. Dead trees were observed adjacent to the landfill. No combustible gas was found on or adjacent to the site indicating that very little anaerobic decomposition was taking place in the refuse. The trees had apparently been killed by soil eroding from the site.

Holyoke Sanitary Landfill #2, Holyoke, Massachusetts

This landfill operated from 1969 through 1973. It contains municipal refuse mixed with incinerator ash to depths of 120 feet in some places.

Of interest at this site were some black cherry trees growing adjacent to the refuse on virgin soil. A good relationship can be seen between death of black cherry and the percent of combustible gas in the soil atmosphere. Under two dead black cherry trees combustible gas in the root zone averaged $10\frac{1}{2}$ percent of the soil atmosphere at a three-foot depth. Combustible gas concentrations were higher near the tree which had died this year as compared with the tree which had been dead for over a year. Under a live black cherry, twenty feet from the dead trees, no combustible gas was found (Table I-22).

There was very little vegetation growing on the landfill. Nothing was planted and very small patches of voluntary weed species were seeding themselves. The cover material on the landfill was very dry and rocky; no topsoil had been put on it. In some areas the cover had eroded exposing the refuse.

TABLE I-22. PERCENT COMPOSITION* OF SOIL GASES AT LIVING AND DEAD BLACK CHERRY TREES

HOLYOKE SANITARY LANDFILL #2, HOLYOKE, MASSACHUSETTS

	Living Cherry		Dead Cherry	
Sample Depth	1'	3'	1'	3'
O_2	19	-	19	-
CO_2	0	-	½	-
Combustible Gas	-	0	-	10½

*Average of 1-7 readings

Erlton Park, Cherry Hill, New Jersey

This 9-10 acre completed sanitary landfill was formerly a sand and gravel pit. General municipal refuse was deposited here, beginning in 1963, to a depth of ten to sixty feet. Dumping was completed in 1970, and efforts to turn the site into a park were begun.

It appeared that less than half of the original trees planted at this park in 1974 were still alive. However, today's tests did not indicate any particular relationship between the presence or absence of combustible gas in the root zone and death or life of the vegetation (Table I-23). In most instances no combustible gas was found in the root zones of either the live or the dead trees. The high rate of tree death may have been due to poor tree-planting practice.

Hard soil layers were noted below the one-foot depth over much of the park. These layers may be keeping the gas from the tree roots and sending it to the vents around the periphery of the former landfill.

TABLE I-23. PERCENT COMBUSTIBLE GAS IN SOIL GASES AT LIVING AND DEAD TREES

EARLTON PARK, CHERRY HILL, NEW JERSEY

	Living Trees						Dead Trees								
	Two-Needle Pine		Poplar		Spruce		Two-Needle Pine			Poplar			Fir	
Sample Depth	1'	1½'	1'	2'	1'	2'	1'	2'	3'	1'	2'	3'	1'	2'
	0	<1	0	0	0	0	0	0	>50	0	0	0	0	0

Kenilworth Demonstration Landfill, Washington, D.C.

The completed landfill is about thirty feet deep and covers approximately 250 acres. It was started in 1942 with only incinerator ash. From 1969 to 1970 a project described as a period of model landfill operations was conducted during which time raw household refuse, as well as incinerator ash, were deposited. The entire area was then completed with a final twenty-four to thirty inch deep soil cover.

Between 1970 and 1975 about 200 trees were planted. These included red oak, sugar maple, and willow. The trees were not irrigated after planting. At least fifty percent of the trees showed signs of chlorosis with many of these being partially or completely defoliated at the time of our visit. Combustible gas checks in the root zones of all but two trees failed to reveal combustible gas. Many of these trees had apparently died from lack of water. The two trees with combustible gas in the root zone were entirely defoliated. A relation between dead trees and the presence of combustible gas existed in some, but not all instances (Table I-24).

TABLE I-24. PERCENT COMPOSITION* OF SOIL GASES AT LIVING AND DEAD TREES

KENILWORTH DEMONSTRATION LANDFILL, WASHINGTON, D.C.

	Living Trees		Dead Trees	
	Sugar Maple	Sweetgum	Sugar Maple	Sweetgum
Sample Depth	1'	1'	1'	1'
O_2	18	-	5	-
CO_2	0	-	12	-
Combustible Gas	0	0	>5	0

*Average of 1-2 readings

Holtsville Sanitary Landfill, Brookhaven, New York

This former landfill covers approximately fifteen acres. Landfilling began around 1955 in an old sand and gravel pit. All types of refuse were accepted including municipal waste, industrial waste and some burned material. The refuse was placed thirty to forty feet below the ground surface and twenty to thirty feet above the surface over part of the landfill. One to six inches of daily cover were spread over the refuse at the end of each day's landfilling operation. The future of this landfill as a park was considered when the final cover was being spread. One foot of sand was placed directly over the refuse and one foot of loam was spread over the sand for the promotion of good grass growth.

Over the former refuse fill area there is a general growth of grass and weeds. Grasses appear to dominate. The area is presently unused, but it is to be developed into a park. There is a parking lot to the south of the fill area and a wood lot on the west side. Dead and dying oaks and pines were observed on the south and west sides adjacent to the refuse.

An excellent relationship (Table I-25) was found between the presence of combustible gas in the soil and the death of deeper rooted vegetation (oak and pines approximately twenty-five years old) adjacent to the landfill. No combustible gases were found in the root zone of viable vegetation, but high concentrations were found in the root zones of the dead trees adjacent to the landfill.

TABLE I-25. PERCENT COMPOSITION* OF SOIL GASES AT LIVE AND DEAD RED OAKS

HOLTSVILLE SANITARY LANDFILL, HOLTSVILLE, NEW YORK

	Live Red Oaks				Dead Red Oaks			
	First Tree		Second Tree		First Tree		Second Tree	
Sample Depth	1'	3'	1'	3'	1'	3'	1'	3'
O_2	-	12	-	18	-	4	-	12
CO_2	-	9	-	0	-	28	-	10
Combustible Gas	0	-	0	-	40	-	>50	-

*Average of 1-3 readings

Kings Park Sanitary Landfill, Smithtown, New York

The twenty-three acre landfill, which was begun in 1971 in a former sand and gravel pit, was still in operation at the time this data was collected. The refuse is of a general municipal type and averages about sixty feet in depth. No vegetation was observed growing on the landfill.

Adjacent to the landfill, on the south side, many dead large oak trees were observed in a woodlot, located between the landfill and Old Northport Road. A dead white oak about thirty feet tall was compared with a living white oak of about the same size. Both trees were located in the woodlot. A dead hemlock six feet tall was compared with a living hemlock seven feet tall. Both hemlocks were planted in 1970 by the city on the edge of the woodlot nearest the road. Soil atmosphere concentrations of combustible gas and carbon dioxide were found in much greater concentrations in the root zones of the dead trees than in the root zones of live trees. Oxygen concentrations in the soil were much lower at the dead trees than at the live trees (Table I-26).

TABLE I-26. PERCENT COMPOSITION* OF SOIL GASES AT LIVE AND DEAD TREES

KINGS PARK SANITARY LANDFILL, KINGS PARK, NEW YORK

	Live Trees				Dead Trees			
	White Oak		Hemlock		White Oak		Hemlock	
Sample Depth	1'	3'	1'	3'	1'	3'	1'	3'
O_2	-	11	-	20	-	4	-	$6\frac{1}{2}$
CO_2	-	8	-	2	-	32	-	$19\frac{1}{2}$
Combustible Gas	1-2	-	0	-	>50	-	$7\frac{1}{2}$	-

*Average of 1-3 readings

Huntington Sanitary Landfill, Huntington, New York

It had been reported that many large oak trees adjacent to this landfill had been killed. An on-site investigation revealed dead trees adjacent to, and around most of the landfill. The incinerator ash and municipal refuse had been placed in a fifty-five foot deep former sand and gravel pit. An area near the southeast corner of the landfill along Town Line Road was chosen for this investigation.

A comparison of the soil atmospheres at the living and dead oak trees adjacent to the landfill (Table I-27) show that extremely high carbon dioxide and combustible gas readings were associated with the dead oaks. Generally lower oxygen concentrations were found in the soil atmospheres at the dead trees than at the live trees. In many cases it was found that the soil beneath the dead trees was septic at the depth of six inches while that beneath the live trees was aerobic. The dead trees on the west side of Town Line Road closest to the landfill didn't have any leaves. The dead trees on the east side of the road still held their dead leaves indicating that the trees farthest from the landfill had died more recently than those nearer the landfill.

Soil temperatures were higher where the higher combustible gas and carbon dioxide and low oxygen concentrations were found (Table I-27).

A limited number of vertical convection vents had been installed along the southern end of the landfill, but trace amounts of combustible gas were found 130 feet from the landfill in the adjacent wood lot. The soil around this landfill is very sandy. This apparently facilitates the movement of the gases generated within the landfill into the adjacent undisturbed land.

TABLE I-27. PERCENT COMPOSITION* OF SOIL GASES AND SOIL TEMPERATURES** AT LIVING AND DEAD TREES
HUNTINGTON LANDFILL, HUNTINGTON, NEW YORK

	Living Trees				Dead Trees			
	Red Oak		Scarlet Oak		Red Oak		Scarlet Oak	
Sample Depth	1'	3'	1'	3'	1'	3'	1'	3'
O_2	-	12	-	-	-	8½	-	8
CO_2	-	9½	-	-	-	35	-	40
Combustible Gas	4	-	0	-	50	-	30	-
Temperature °F	64	-	58	-	65	-	78	-

*Average of 1-3 readings
**Single readings

Bethpage Sanitary Landfill, Oyster Bay, New York

This forty acre landfill is located in a very sandy soil region of Long Island. The landfill contains general municipal refuse, ash, and demolition debris which has been placed in a former sand and gravel pit that averages about forty feet deep. In many areas the refuse is piled to a total depth of sixty to eighty feet. Adjacent to the easterly side of the landfill and across Winding Road is a bridle trail. It was noted that most of the mature red and white oaks (40 to 50 feet in height) in the area were dead, but most of the understory vegetation was living.

Near the dead oaks, both combustible gas at one foot and carbon dioxide at three feet were very high (35 to 40%) and oxygen readings at three feet were low (5 to 10%). Landfill gases appear to have migrated to about seventy feet from the landfill. No live trees were accessible for comparison with the dead oaks.

It appears that the demise of the native trees in this area was due to the pollution of the soil by gases migrating underground from the landfill across the street. The understory vegetation may still be living because of its shallower root system.

Dcb - TEMPERATE CONTINENTAL COOL SUMMER CLIMATE

Roussel Park, Haines Road, Nashua, New Hampshire

This site had been an open dump which was covered with five feet of gravel, on top of which was placed six inches of loam. The refuse is ten to twelve feet thick and consists mostly of municipal type refuse. The cover material has been planted with grass which was observed to be providing adaquate cover. Two baseball parks and a monument have been established on the site.

Correlation between the presence of combustible gas and death of American elm and slippery elm (located adjacent to the refuse) was not very good. At a depth of three feet, comparable concentrations (0% to 40% of the soil atmosphere) of combustible gas were found under healthy trees and dead trees. There was also a dead tree near which no combustible gas was found. The possibility exists that combustible gas, present at an earlier time, killed the tree, and has subsequently left this tree's root zone. Dutch elm disease is also very prevalent in this region, although its characteristic symptoms were not noticeable on this dead tree.

In the root zone of one slippery elm there was found between fifteen percent and thirty-five percent combustible gas in the soil atmosphere at 2' and 3' respectively. There was a small branch on this tree with yellowing leaves which appeared symptomatic of Dutch elm disease.

Oxygen concentrations at one foot were about normal (18%) under both living and dead trees. Under one dead elm a CO_2 concentration of 2.5% was recorded at a one-foot depth. The highest combustible gas concentrations (40%) were recorded at this spot at a three foot depth, but no combustible gas was noted at a one-foot depth in this area.

In summary, correlation between the presence of landfill gas in the soil atmospheres and dead trees was poor at this site.

Guilderland Landfill, Guilderland, New York

This landfill was still operating when this data was collected. The area of the landfill where the data was collected was completed in 1971. The landfill contains municipal refuse on top of which there is about two feet of cover material. This area had been seeded with rye grass but with poor success.

Volunteer species were observed growing on the site, most notably: quaking aspens, staghorn sumac, milkweed, and Queen Anne's lace. This volunteer vegetation, along with the rye grass, was observed to be occurring in isolated clumps with bare and sparsely vegetated areas between. The areas where the vegetation was growing well were compared with the areas where the vegetation was growing poorly or not at all. Combustible gas and CO_2 concentrations at a depth of one foot in the soil were considerably higher where the vegetation wasn't growing well. Oxygen concentrations at a one foot depth were very low in the poor growth areas averaging only 2.5% of the soil atmosphere as compared with 16.4% in the good growth areas (Table I-28). The data indicates that the composition of the soil atmosphere on this landfill was probably playing a major role in determining where the vegetation was able to establish itself.

TABLE I-28. PERCENT COMPOSITION* OF SOIL GASES AT GOOD AND POOR GROWTH VEGETATION

GUILDERLAND LANDFILL, GUILDERLAND, NEW YORK

	Good Growth	Poor Growth
Sample Depth	1'	1'
O_2	16½	2½
CO_2	2½	34½
Combustible Gas	3	40½

*Average of 4 - 10 readings

City of Auburn North Division Street Sanitary Landfill, Auburn, New York

This landfill was operating at the time this data was collected. The area on the landfill with which this report is concerned was completed about fifteen years ago and is estimated to contain about twenty feet of municipal refuse. The cover appeared to range in depth from two to three feet. Grass was doing very well on the site as were many of the trees which had become established on the site.

Of particular interest was a row of willow trees which were showing wide variations in growth. There was a negative correlation between the height of the willow trees and the concentrations of combustible gas in the soil atmosphere. There were three distinct height categories with different gas concentrations in their root zones. At the two-foot depth, the willows which were twenty feet high had an average of less than one percent combustible gas in the soil atmosphere; the ten-foot high trees had an average of 8.5% combustible gas at the two-foot depth; and in the area where the trees had died and been removed, the soil atmosphere contained an average of 30.5% combustible gas at a two-foot depth (Table I-29).

The fact that increased combustible gas in the soil atmosphere correlated with a decrease in the height of the tree may indicate an adverse response to the presence of combustible gas in the soil atmosphere.

TABLE I-29. PERCENT COMPOSITION* OF SOIL GASES AT WILLOW TREES SHOWING VARIOUS GROWTH CHARACTERISTICS

CITY OF AUBURN NORTH DIVISION STREET SANITARY LANDFILL, AUBURN, NEW YORK

	20' Tall and Healthy		10' Tall		Dead and Removed	
Sample Depth	1'	2'	1'	2'	1'	2'
O_2	20	-	19	-	$18\frac{1}{2}$	-
CO_2	0	-	$\frac{1}{2}$	-	$\frac{1}{2}$	-
Combustible Gas	-	1	-	$8\frac{1}{2}$	-	$30\frac{1}{2}$

*Average of 2-4 readings

South Eastern Oakland Incinerator Authority, Oakland County, Michigan

This landfill was completed in a former sand and gravel pit in 1968 and contains an average of about thirty-five feet of municipal refuse mixed with incinerator ash. This landfill has had problems with landfill gases migrating into adjacent property, particularly on the western edge. It was in this area that this data was collected, in and around a row of lombardy poplars planted adjacent to the landfill. Most of the lombardy poplars were dead at the time that this data was collected.

A negative correlation between weed and grass growth and combustible gas present at one foot was very good. There was no combustible gas present at one foot where the weeds and grass were growing well. At spots where there was no weed or grass growth, combustible gas averaged twenty-two percent of the soil atmosphere at the one foot depth. Also in these bare areas O_2 averaged nine percent of the soil atmosphere and CO_2 averaged 4.5% of the soil atmosphere at the one foot depth. These are, respectively, far below and above normal soil gas concentrations. When these gas concentrations are compared with those found in the areas where grass and weeds were growing well a sharp contrast is observed (Table I-30).

All the lombardy poplars which have died and subsequently sprouted were found to contain considerable amounts (between 5 and 50% of the soil atmosphere) of combustible gas in the root zone at the two-foot depth. At no time was a dead tree observed with no combustible gas in the soil atmosphere. Two mature (70 ft. tall) black oaks were observed to be in rapid decline within twenty feet of the landfill. At no point at a three foot depth near these trees was less than fifty percent combustible gas found in the soil atmosphere.

A trend was seen here in the pattern of necrosis on the three species of plants observed dying at this site. When combustible gas was present in the soil and necrosis was seen on the foliage, the dieback of the leaves usually began at the tips of the branches and progressed down towards the base of the plant.

TABLE I-30. PERCENT COMPOSITION* OF SOIL GASES AT GOOD GROUND COVER AND NO VEGETATION GROWTH AREAS

SOUTHEAST OAKLAND INCINERATOR AUTHORITY LANDFILL, OAKLAND, MICHIGAN

	Weeds and Grass Growing Well	No Weed or Grass Growth
Sample Depth	1'	1'
O_2	20	9
CO_2	0	$4\frac{1}{2}$
Combustible Gas	$\frac{1}{2}$	$22\frac{1}{2}$

*Average of 2-9 readings

Cereal City Landfill #1, Battle Creek, Michigan

This landfill has been operating since 1956. It contains an average of about twenty-four feet of municipal refuse covered with about two feet of sandy soil where completed. No attempts had been made to vegetate this cover. This landfill has a history of gas migrating into adjacent property. This report concerns a row of red pine trees which had been transplanted to the northern edge of the landfill less than ten feet from the refuse in this former sand and gravel pit.

There is a negative correlation between the occurrence of landfill gases and the health of the trees. Where the trees were dead for over two years, the average percent combustible gas concentrations in the soil atmosphere were 22.7% at the one-foot depth and 49% at the three-foot depth. The O_2 concentrations averaged 12% and the CO_2 averaged 17.5% at a depth of one foot. In the area where the trees were living but experiencing some needle necrosis, the combustible gas averaged .25% at a one-foot depth and 15% at a three-foot depth. The CO_2 and O_2 concentrations were, respectively, 6.5% and 19.5% at a depth of one foot (Table I-31).

TABLE I-31. PERCENT COMPOSITION* OF SOIL GASES AT LIVING AND DEAD RED PINE TREES

CEREAL CITY LANDFILL, BATTLE CREEK, MICHIGAN

	Living Red Pine**		Dead Red Pine**	
Sample Depth	1'	3'	1'	3'
O_2	19½	-	12	-
CO_2	6½	-	17½	-
Combustible Gas	½	15	22½	49

*Average of 1-8 readings

**Weeds and grass growing well near live tree, no grass or weed growth near dead tree.

Cereal City Landfill #2, Battle Creek, Michigan

This landfill has been in operation since 1956. It contains an average of about twenty-four feet of municipal refuse covered with about two feet of sandy soil. No attempts have been made to vegetate this cover. This landfill has a history of gas migrating onto adjacent property. This report is concerned with a row of mixed hardwood and coniferous trees located along the southwest corner of the landfill. Most of these trees, adjacent to this former sand and gravel pit, were observed to be in decline and many were dead.

There appears to be an excellent correlation between the presence of combustible gas in the root zone of the planted trees and death or decline of these trees. This was found to be true for white spruce, Douglas fir, white fir and shagbark hickory. The amount of combustible gas in the root zones of these trees at the one foot depth varied between 5% and 50% (with a mean of 25.6%) of the atmosphere. There were two live white spruce trees under which the combustible gas concentrations ranged from 10% to greater than 50% (with a mean of 29.5%) of the soil atmosphere at the one-foot depth. These trees may not have been exposed to the landfill gases as long as the trees which had been killed, or they could be resistant or have shallow roots.

A very putrid-smelling, hard soil layer, three inches thick, was present in the virgin soil where high combustible gas concentrations were found. The top of this layer was found five inches below the surface, and it was not present where combustible gas was not found.

Kalamazoo County Landfill, Kl Avenue, Oshtemo Township, Michigan

This landfill has been operating since 1965. It contains municipal and light industrial refuse ranging in depth from eighteen to forty feet. The final cover was generally two feet thick, but noticeably thinner in some areas. The completed landfill was planted with clover and fescue with reasonable success. An area which had recently been planted with Kentucky 31 Fescue was doing very poorly; the cover material in this area was very thin and dry.

In one area of the landfill a quaking aspen, which was showing no signs of stress, had an average of 8.4% combustible gas in the soil atmosphere at a one foot depth, O_2 comprised 18.5% and CO_2 3.5% of the soil atmosphere at a one foot depth.

Do - TEMPERATE OCEANIC CLIMATE

East Campus, University of Washington, Seattle, Washington

From 1926 to 1955 parts of this 150 acre peat bog area served as an open-burning dump for the city of Seattle. In 1956 "modern" sanitary landfill methods were started. The rate of filling the marshland accelerated from the late 50's until 1966 when filling ceased. However, a series of surface cover filling, grading and seeding operations altered the landscape, until 1971, when all but minimal maintenance activities ceased. Today the central part of this area supports a grassy prairie-like cover bordered by peat islands, cattails and occasional trees along the shoreline.

Settlement over the area has been extensive. It is reported that portions of the site dropped six feet between 1971 and 1975. Part of this settlement is believed to be due to the decomposition and compression of the underlying former peat bogs.

Gas checks over the grasslands area revealed no combustible gas to a depth of three feet in an area where the grass and weed ground cover was growing very well. In an area within forty-five feet of the good growth area, where no grass or other ground cover was growing, combustible gases were found at high concentrations (>15%) at the one, two and three-foot depths. The soils in the no-growth area below the four inch depth were dark and emitted a septic odor. The soils in the good growth area were not septic. They emitted the normal pleasant soil odor. The areas in the grasslands which did not contain any vegetation also exhibited numerous cracks in the surface. In many cases it was noted that the unpleasant odors of the gases of anaerobic decomposition were being emitted from these cracks. It was reported that children have frequently set fire to these gases.

In random checks of the soil atmospheres in the root zones of various trees growing over the refuse filled area outside the grasslands section, combustible gases were not generally found in the atmosphere of soil less than two feet deep.

In the vicinity of the golf driving range, where a number of trees were checked, combustible gases were found in a number of cases at the two-foot depth and below. These combustible gases were present although the last refuse filling was reported to have been completed in this area prior to 1950. The trees in general appeared to be growing fairly well in this area.

In general, there was an excellent correlation in the "grasslands area" between poor and no vegetation ground cover and the presence of combustible gases within one foot of the surface. Where the combustible gases were below the two-foot depth the ground cover was doing very well.

Genesee Street Landfill Park Development, Seattle, Washington

This former landfill covers approximately sixty acres. Filling began in 1947 and was completed about 1968. The area north of Genesee Street was completed in 1963. That south of Genesee Street was completed in 1968. General landfill refuse was deposited in the fill along with a large amount of demolition debris and ash from the open burned refuse. The refuse varies in thickness from a few feet to about thirty feet. The cover material depth ranges from about two to about six feet. The material used for final cover was mostly glacial till. Substantial settlement has been reported during the last few years, along with some mounding of ground water in part of the fill.

Over the former refuse fill area there is a general growth of grasses and weeds. Grasses appear to dominate. The area is mowed about twice each year. The north end of the field area is occasionally used as a parking area. Most of the rest of the fill area is unused in any developed or planned manner. There are some peat deposits and soft clays beneath part of the fill area. It is believed that these peat deposits may be compacting due to the subcharging by the refuse and cover material.

Scattered barren spots were noted over the surface of the ground at various locations. These barren areas frequently contained many surface cracks, and occasionally the odors of the gases of anaerobic decomposition of organic matter in the landfill were detected. The soils from these barren combustible gas-laden areas were found to be soft, wet, dark-colored, and emitting septic odors. The soils where good grass and tree growth were taking place did not contain combustible gas, was dry and hard, and did not emit septic odors.

An oval area approximately 20'/9', had no vegetation growing on it. It was found to have a very high combustible gas concentration (>15%) at one foot. Soil from the six inch to eight inch depth was dark colored, had a putrid odor, and was anaerobic. The soil $16\frac{1}{2}$ feet away in an area of good growing vegetation ground cover showed no combustible gases at the one and two-foot depths. Soil samples taken to an eleven inch depth were light-colored, friable, and exhibited no anaerobic odor.

No combustible gas was found at the three-foot depth under a big-leaf maple tree growing near the sidewalk along the north side of Genesee Street. At about sixty feet to the north a barren area, around 12'/27', was checked for combustible gas. It was found to contain high concentrations of combustible gas in the soil atmosphere.

Overall, an excellent correlation was found between the presence of combustible gases in the soil and the lack of surface vegetation. No combustible gases were found in the root zone of viable vegetation.

Day Island Landfill, Eugene, Oregon

This sixty-acre landfill is located in a former sand and gravel pit on the northeast side of the Willamette River. Between 1963 and 1974 the area was filled to depths ranging from twelve to thirty feet with general municipal refuse and construction rubble.

Currently a good general grass and weed growth covers most of the landfill. Some of the grasses were three to four feet high. However, there were numerous small areas where no ground cover existed. The no-growth station was found to have high concentrations of combustible gas at the one-foot depth, and the soil was septic at the three-inch depth. At a nearby good growth station there was no combustible gas to sixteen inches and the soil was aerobic (Table I-32).

The soil atmospheres of trees planted for landscaping purposes was checked, and combustible gas was found in the root zone of a dead tree, but it was not present in the root zones of two living trees. The soil was also septic in the root zone of the dead tree, but aerobic in the root zones of the live trees.

An area of dead and dying trees east of the landfill was surveyed. Here high concentrations of combustible gas were found in the soil atmospheres within seventy feet of the landfill where the trees were dead or dying. One-hundred and twenty feet from the landfill, the fifty-to sixty-foot tall trees were growing very well, and no combustible gas was present in the soil atmospheres.

As can be seen from Table I-32, there is an excellent correlation between the presence of landfill gases in the vegetation root zone and poor or no vegetation growth.

Soil temperatures were measured on and off the landfill and in gas and no-gas areas. The results are plotted in Figure I-2. In general, the temperature decreased with increasing depth. The highest temperatures were found where combustible gases were present on and off the landfill. The lowest temperatures were found off the landfill in the area where no combustible gases were present.

TABLE I-32. PERCENT COMBUSTIBLE GAS IN SOIL ATMOSPHERES AT LIVING, DYING, AND DEAD VEGETATION

DAY ISLAND LANDFILL, EUGENE, OREGON

	Sample Location	Description of Vegetation	Approximate % Combustible Gas Concentration At Various Depths	Soil Condition
Living Vegetation	Adjacent Ld-Fl	Healthy trees and grass.	0 at 1' and 3'	-
	On Ld-Fl	Grass and weed cover growing very well.	0 at 1' and 16"	Very hard below 16"
	On Ld-Fl	A living but not thriving black oak planted two years previous.	0 at 1' and 2'; >15 at 3'	Topsoil; light gray-brown, pleasant odor, barely moist.
	On Ld-Fl	A living but not thriving broadleaf maple planted two years previous.	0 at 1' and 2'	Hard ground below 2'
Dead and Dying Vegetation	Adjacent Ld-Fl	Grass and weeds doing poorly Many large dead trees.	>15 at 3'	-
	Adjacent Ld-Fl	Good grass cover. Dead white ash & broadleaf maple trees.	0 at 1'; 5-15 at 3'	-
	Adjacent Ld-Fl	Scattered live brush & grass Quite a bit of barren soil; Scattered dead & dying trees.	5-15 at 1' >15 at 3'	-
	On Ld-Fl	Barren, no vegetation. Barren, no vegetation.	5-15 at 1' and 16"	Septic odor, dark colored & damp; very hard below 16"
	On Ld-Fl	Dead red oak that was planted two years previous.	5-15 at 1'; >15 at 30"	Septic odor, black and wet

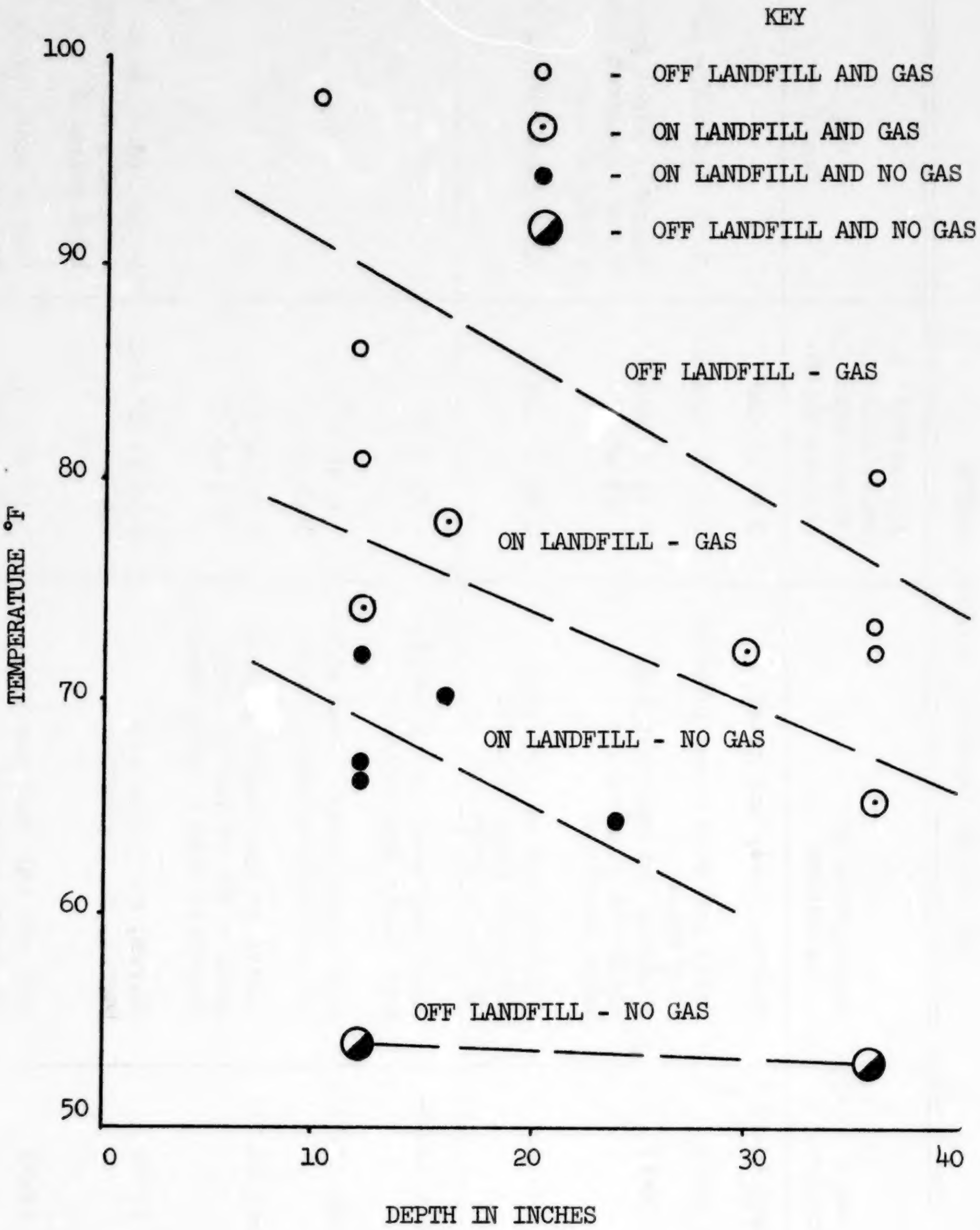

Figure I-2. Soil temperatures, Day Island Landfill, June 24, 1976

John Fowler's Farm, West Salem, Oregon

Approximately two acres of John Fowler's wheat field is located over about twenty feet of demolition waste that was deposited in 1968-69. This is a small section of a much larger wheat field. The wheat growing over the former landfill appeared to be almost as healthy as that growing in the virgin soil, non-refuse area. Combustible gas was found at less than half the test stations and then only at very low concentrations. However, there were some areas where surface settlement had been so extensive that the area could not be cultivated until it was refilled and replanted. Farmer Fowler also reported that he experiences difficulty in maintaining an adequate water supply in the soil over this refuse area because the shallow soil cover tends to dry out quickly between waterings.

Table I-33 summarizes the data obtained from the test stations. The soil was very hard at many of the test stations located over the former demolition landfill.

TABLE I-33. PERCENT COMBUSTIBLE GAS IN SOIL ATMOSPHERES IN WHEAT FIELD

JOHN FOWLER'S FARM, WEST SALEM, OREGON

Sample Location	Vegetation Quality	Combustible Gas Readings	Soil Condition
On Ld-Fl	13-15" tall wheat	0 at 3'	Hard to very hard
On Ld-Fl	10-21" tall wheat	Minor at 21"	Damp and dark brown extremely hard below
On Ld-Fl	13-31" tall wheat	0 at 3'	Soft
On Ld-Fl	14-20" tall wheat	0 at 8"	Rocklike at 8 inch depth
On Ld-Fl	11-23" tall wheat	0 at 1'	Hard object at 1'
On Ld-Fl (In Settled Area)	Scattered weeds (in settled area)	Trace at 2'	Soft to 33"
Adjacent Ld-Fl	12-27" tall wheat	0 at 3'	Varying from hard to soft

NOTE: Many small green aphid-like insects and many potato beetles were visible on the wheat.

H - HIGHLAND CLIMATE

Freemont Park, Idaho Falls, Idaho

This 15-17 acre site was a dump where open burning was practiced for forty years prior to it being converted into a sanitary landfill in 1970. Landfilling with municipal refuse was practiced from 1970 through 1972. The unburned refuse ranged in depth from 0 to 15 feet. After the landfilling ceased the process of converting the site into a park began and was still proceeding at the time that this data was collected. Due to variability in the composition of the refuse, a good deal of variability in the stability of the soil and landfill gas concentrations would be expected over the site.

In general, the grass was growing well throughout the park. However, many trees seemed to be having growth problems. Many dead and dying specimens were observed. Some of the deaths were apparently due to poor planting practices; in one case the root ball of a ten-foot high cypress tree was only half buried.

Data was collected, comparing trees which appeared to be dead or severely stressed with trees of similar size that were not exhibiting any strees symptoms (Table I-34). Trees that didn't exhibit any evidence that they had been subjected to poor planting practices were chosen for comparison. The dying and dead trees included: a nine-foot high blue spruce experiencing about ninety percent needle loss, a fifteen-foot high dead basswood tree and a fifteen-foot high dead white spruce. These dead and dying trees were compared with trees of the same species that appeared healthy. None of these trees were recent transplants to the park.

The data collected doesn't indicate that there is any direct relationship between the demise of the trees and the occurrence of landfill gas pollution in the soil of this park.

TABLE I-34. PERCENT COMPOSITION* OF SOIL GASES AT GOOD AND POOR GROWTH TREES

FREMONT PARK, IDAHO FALLS, IDAHO

	Good Tree Growth			Poor Tree Growth		
	Basswood	White Spruce	Blue Spruce	Basswood	White Spruce	Blue Spruce
Sample Depth	1'	1'	1'	1'	1'	1'
O_2	18½	-	8	7½	10	13
CO_2	2	-	8	35	10	3
Combustible Gas	0	0	0	3	0	0

*Average of 1-3 readings

Red Baron Alfalfa Field, Idaho Falls, Idaho

This landfill was completed in 1970 with ten to fifteen feet of municipal refuse. Alfalfa and rye grass were planted in 1976, but neither grew very well on the landfill. Settlement was observed to be severe over most of the site, making cultivation difficult. The person responsible for farming the area felt that settlement was not the only problem. He noted that the alfalfa didn't grow well over the refuse.

The entire area being farmed was not on refuse. It was observed that the alfalfa planted off of the landfill was growing very well, reaching two to three feet in height. The alfalfa growing over the refuse was difficult to find. What was growing was mostly less than one foot in height. Weeds and grass were also growing better in the area off the refuse.

Comparisons were made of the soil atmospheres in the area over the refuse and that adjacent to the refuse (Table I-35). The soil appeared to be of better quality on the virgin land. The cover on the landfill also appeared to be a little shallow, only about a foot in some areas. Combustible gas and CO_2 concentrations were very high beneath the poor alfalfa growth and zero beneath good growth.

This site exemplifies the problems that can occur when trying to grow vegetation on a completed sanitary landfill. These problems include: settlement, poor soil conditions, difficulty in maintaining a satisfactory water balance, and pollution from landfill gases. It appears that a combination of these factors is probably responsible for the vegetation growth problems encountered on this former landfill.

TABLE I-35. PERCENT COMPOSITION* OF SOIL GASES AT GOOD AND POOR GROWTH ALFALFA

RED BARON ALFALFA FIELD, IDAHO FALLS, IDAHO

	Good Alfalfa Growth (Adjacent to landfill)	Poor Alfalfa Growth (On landfill)
Sample Depth	3'	3'
O_2	19½	5½
CO_2	0	34½
Combustible Gas	0	>50

*Average of 2-3 readings

Idaho Falls Child Development Center, Idaho Falls, Idaho

The Child Development Center is a special school for handicapped children. The school was constructed on a former sanitary landfill in 1971. The landfill operated from 1961 to 1964 depositing an average of about eight feet of municipal refuse. Settlement had damaged the building to the extent that a new roof had to be put on the structure.

Problems were reported with some of the trees that were planted when the site was landscaped in 1971-1972. Two blue spruces were said to be having problems growing. Since planting, the trees have grown very poorly exhibiting only sparse growth during most of the years.

An on-site inspection revealed that the most probable reason for the poor growth was a cement factory located across the street from the center. The needles were covered with cement dust to the extent that shaking the branches caused a cloud of dust to rise. Combustible gas readings near both trees were very low, ranging from zero to five percent at the three foot depth. Oxygen and carbon dioxide readings at the same depth were about normal, oxygen being around twenty percent and carbon dioxide 0.5 percent or less.

APPENDIX J

FIELD SURVEY DATA-MINERAL CONSTITUENTS AND SOIL CHARACTERISTICS

TABLE J-1. REGION Ar - TROPICAL, WET

Soil Constituent	Top Soil	
	No Gas	Gas
lb/acre		
Magnesium	782	800
Phosphorus	6	6
Potassium	134	130
Calcium	12,125	9,750
Ammonia-nitrogen	8	15
Nitrate-nitrogen	119	108
Organic matter	3.9	2.0
Moisture	-	-
ppm		
Iron	Tr.	Tr.
Manganese	6.25	8.75
Copper	0.90	0.65
Zinc	0.70	1.75
Boron	0.31	0.34
Iron/Manganese	-	-
Conductivity	3.7	4.2
pH	7.7	7.8
percent		
Sand	65.0	55.0
Silt	22.0	28.0
Clay	13.0	17.0

TABLE J-2. REGION BS - STEPPE

Soil Constituent	Top Soil	
	No Gas	Gas
lb/acre		
Magnesium	800	800
Phosphorus	2	3
Potassium	400	400
Calcium	7,200	7,800
Ammonia-nitrogen	2.4	1.0
Nitrate-nitrogen	20.0	17.0
Moisture	9.5	10.9
Organic Matter		
ppm		
Iron	2.4	-
Manganese	2.0	-
Copper	0.32	-
Zinc	0.60	-
Boron	1.95	2.0
Iron/Manganese	1.2	-
Conductivity	< 0.10	< 0.10
pH	8.5	8.4
percent		
Sand	40	44
Silt	34	36
Clay	26	20

TABLE J-3. REGION BW - ARID, DESERT

Soil Constituent	Top Soil		Sub Soil	
	No Gas	Gas	No Gas	Gas
lb/acre				
Magnesium	800	800	800	800
Phosphorus	106	176	152	227
Potassium	282	297	328	253
Calcium	1,662	1,700	1,683	1,850
Ammonia-nitrogen	11.8	69.3	17.3	17.0
Nitrate-nitrogen	2.8	12.3	3.7	2.0
Moisture	-	-	-	-
Organic Matter	1.6	2.1	1.3	1.5
ppm				
Iron	0.63	0.50	0.81	3.00
Manganese	8.3	12.7	33.7	37.0
Copper	0.25	0.42	0.38	0.25
Zinc	0.71	0.70	0.91	5.00
Boron	0.34	0.55	0.86	0.30
Iron/Manganese	0.08	0.39	0.02	0.09
Conductivity	0.34	0.99	0.79	0.44
pH	8.2	8.0	8.1	8.2
percent				
Sand	59.8	66.0	61.0	68.0
Silt	27.8	21.7	26.7	22.0
Clay	12.4	12.3	12.3	10.0

TABLE J-4. REGION Cf - SUBTROPICAL, HUMID

Soil Constituent	Top Soil		Sub Soil	
	No Gas	Gas	No Gas	Gas
lb/acre				
Magnesium	164	149	224	143
Phosphorus	63	60	9	9
Potassium	103	82	49	72
Calcium	827	1,248	411	310
Ammonia-nitrogen	8.5	4.5	3.9	10.0
Nitrate-nitrogen	13.7	11.3	3.6	10.0
Moisture	9.3	8.6	5.9	8.5
Organic Matter	1.9	2.1	0.8	1.2
ppm				
Iron	55.2	70.8	24.5	102.4
Manganese	19.5	23.2	11.4	25.5
Copper	0.68	1.16	0.76	1.00
Zinc	2.8	14.3	1.9	7.5
Boron	0.27	0.26	0.22	0.24
Iron/Manganese	2.83	3.05	2.15	4.02
Conductivity (Mols)	0.11	0.13	0.10	0.10
pH	5.6	6.0	5.8	5.8
percent				
Sand	66.7	76.3	66.7	66.7
Silt	18.3	12.6	13.3	14.7
Clay	15.0	11.0	20.0	18.7

TABLE J-5. REGION Cs - SUBTROPICAL, DRY SUMMERS

Soil Constituent	Top Soil	
	No Gas	Gas
lb/acre		
Magnesium	2,308	2,417
Phosphorus	1,074	1,130
Potassium	163	1,440
Calcium	3,275	2,508 *
Ammonia-nitrogen	4.8	9.0*
Nitrate-nitrogen	27.8	29.6
Moisture	5.1	7.6
Organic Matter	22.7	26.8 *
ppm		
Iron	2.4	4.3 *
Manganese	13.6	11.1
Copper	5.09	6.18
Zinc	5.22	7.72 *
Boron	-	-
Iron/Manganese	0.18	0.39
Conductivity	0.84	1.05
pH	7.3	7.0
percent		
Sand	37.3	39.3
Silt	29.3	28.6
Clay	33.3	32.0

*Significant difference at P = 0.05

TABLE J-6. REGION Dca - TEMPERATE, CONTINENTAL, HOT SUMMERS

Soil Constituent	Top Soil		Sub Soil	
	No Gas	Gas	No Gas	Gas
lb/acre				
Magnesium	125	186	51	39
Phosphorus	150	141	73	73
Potassium	80	104	72	86
Calcium	454	645	92	97
Ammonia-nitrogen	4.8	37.1	6.8	35.1
Nitrate-nitrogen	10.6	23.9	10.5	17.4
Moisture	6.3	9.7	8.4	10.8
Organic Matter	1.0	1.7	0.9	0.9
ppm				
Iron	58.2	104.3	57.5	186.4
Manganese	17.5	34.3	11.7	22.4
Copper	3.5	4.3	1.5	1.9
Zinc	5.5	6.3	2.2	2.1
Boron	0.36	0.23	0.18	0.13
Iron/Manganese	3.32	3.04	4.91	8.32
Conductivity (mohs)	0.10	0.18	0.12	0.12
pH	5.7	6.0	5.4	5.7
percent				
Sand	84.7	76.2	85.8	83.2
Silt	8.4	15.7	7.3	10.3
Clay	7.0	8.1	7.0	6.6

TABLE J-7. REGION Dcb - TEMPERATE, CONTINENTAL, COOL SUMMERS

Soil Constituent	Top Soil	
	No Gas	Gas
lb/acre		
Magnesium	209	196
Phosphorus	140	121
Potassium	112	150
Calcium	1,965	2,349
Ammonia-nitrogen	10.5	33.8 **
Nitrate-nitorgen	461.0	471.3
Moisture	14.8	15.8
Organic Matter	3.4	2.2
ppm		
Iron	0.4	62.4
Manganese	4.8	10.8
Copper	0.15	0.45
Zinc	0.80	7.08
Boron	-	0.17
Iron/Manganese	0.08	5.8
Conductivity (mohs)		
pH	5.7	5.9
percent		
Sand	78.3	81.1
Silt	13.1	11.3
Clay	8.6	7.8

** Significant difference at P = 0.01

TABLE J-8. REGION Do - TEMPERATE OCEANIC

Soil Constituent	Top Soil		Sub Soil	
	No Gas	Gas	No Gas	Gas
lb/acre				
Magnesium	800	800	800	800
Phosphorus	166	189	206	136
Potassium	154	114	181	175
Calcium	2,676	2,573	2,760	2,213
Ammonia-nitrogen	2.1	22.7 *	1.7	71.6
Nitrate-nitrogen	23.8	22.0	22.9	52.5
Moisture	8.2	11.4 *	23.7	11.7
Organic Matter	2.2	2.1	2.9	3.5
ppm				
Iron	116.7	162.9	116.0	247.7
Manganese	60.0	75.5	58.3	101.3
Copper	4.7	6.5 *	3.3	6.2
Zinc	10.4	17.0 *	3.1	6.5
Boron	0.34	0.57	0.32	0.34
Iron/Manganese	1.95	2.16	1.99	2.71
Conductivity (mohs)	0.12	0.26 *	0.19	0.28
pH	6.4	6.9	6.5	6.5
percent				
Sand	56.6	49.8	52.3	51.3
Silt	30	24.8		
Clay	16	14.8		

*Significant differences at P = 0.05

TABLE J-9. REGION H - HIGHLANDS

Soil Constituent	Top Soil		Sub Soil	
	No Gas	Gas	No Gas	Gas
lb/acre				
Magnesium	741	753	690	774
Phosphorus	5	8	10	204
Potassium	166	181	95	192
Calcium	8,789	7,608	9,424	8,420
Ammonia-nitrogen	1.9	0.9	1.0	2.0
Nitrate-nitrogen	14.2	17.6	10.0	48.0
Moisture	17.1	16.2	8.8	22.4
Organic Matter	1.5	2.7	2.9	6.5
ppm				
Iron	2.4	2.9	2.4	2.0
Manganese	3.6	13.9	8.4	12.0
Copper	0.28	0.20	0.30	0.40
Zinc	0.85	4.00	0.93	1.60
Boron	6.48	6.70	0.29	1.14
Iron/Manganese	0.67	0.21	0.29	0.17
Conductivity	0.10	0.20	0.11	0.15
pH	8.3	8.1	8.2	8.0
percent				
Sand	54	60.8	76	81
Silt	30	24.8	17	14
Clay	16	14.8	7	5

TABLE J-10. MEAN PERCENT (%) CHANGE IN CONTENT OF CONSTITUENTS OF SOILS FROM 9 CLIMATIC REGIONS AS SOIL PROCEEDED FROM NO-GAS TO HIGH GAS CONCENTRATIONS

Soil Constituent	Ar P.R.	Bs Utah	Bw Des.	Cf S.	Cs Cal.	Dca N.E.	Dcb M.A.	Do N.W.	H Mts.	Mean of 9 Regions
Mg *	+ 2.3	± 0.0	± 0.0	- 9.2	+ 4.7	+ 48.8	- 6.2	± 0.0	+ 1.6	+ 4.6
P	± 0.0	+ 50.0	+ 66.0	- 4.8	+ 5.2	- 6.0	- 13.6	+ 13.9	+ 37.5	+ 16.5
K	- 3.0	± 0.0	+ 5.3	- 20.4	- 11.7	+ 30.0	+ 33.9	- 26.0	+ 9.0	+ 1.9
Ca	- 19.6	+ 8.3	+ 2.3	+ 50.9	- 23.4	+ 42.1	+ 19.5	+ 3.8	- 13.4	- 7.8
NH_3-N	- 9.2	- 15.0	+ 33.9	- 17.5	+ 6.5	+125.5	+ 2.2	- 7.6	+ 23.9	+ 15.9
NO_3-N	+ 87.5	- 58.3	+487.3	- 47.1	+ 87.5	+672.9	+ 221.9	+800.0	- 52.6	+ 239.3
H_2O	-	+ 14.3	-	- 7.5	+ 49.0	+ 54.0	+ 6.8	- 12.7	+ 5.3	+ 15.6
O.M.	- 48.7	- 22.1	+ 31.3	+ 9.4	+ 18.1		- 35.2	- 9.3	+ 79.1	- 2.7
Fe	± 0.0	-	- 20.6	+ 28.3	+ 79.2	+ 79.2	+15500.0	+ 39.6	+ 28.0	+1967.0
Mn	+ 40.0	-	+ 53.0	+ 19.0	- 18.4	+ 96.0	+ 125.0	+ 25.8	+286.0	+ 78.3
Cu	- 27.8	-	+ 68.0	+ 70.5	+ 21.4	+ 22.9	+ 200.0	+ 38.3	- 28.0	+ 45.7
Zn	+150.0	-	- 1.4	+410.0	+ 47.9	+ 14.6	+ 785.0	+ 63.5	+370.0	+ 218.0
B	+ 9.7	+ 2.6	+ 61.8	- 3.7	-	- 36.1	-	+ 67.5	+ 3.4	+ 46.1
Fe/Mn	-	-	+387.5	+ 7.8	+ 116.7	- 8.4	+ 7150.0	+ 10.8	- 68.6	+1085.0
C.	+ 13.5	± 0.0	+191.2	+ 18.1	+ 25.0	+ 80.0	+ 66.7	+117.0	+100.0	+ 67.9
pH	+ 1.3	- 1.2	- 2.4	+ 7.2	- 4.3	+ 5.2	+ 3.5	+ 7.8	- 2.4	+ 1.6
Sand	- 15.4	+ 10.0	+ 10.4	+ 14.4	+ 5.4	- 10.0	+ 3.6	- 12.0	+ 12.6	+ 2.3
Silt	- 27.3	- 5.9	- 21.9	- 31.1	- 2.4	+ 86.9	- 13.7	+ 8.8	- 17.3	- 2.7
Clay	+ 30.8	- 23.0	- 0.8	- 26.7	- 3.9	+ 15.7	- 9.3	+ 10.5	- 7.5	- 1.6

*See page 129 for abbreviation key.

TABLE J-10. (continued)

LIST OF ABBREVIATIONS*

Mg -- Magnesium
P -- Phosphorus
K -- Potassium
Ca -- Calcium
NH_3-N -- Ammonia-nitrogen
NO_3-N -- Nitrate-nitrogen
H_2O -- Moisture
O.M. -- Organic Matter
Fe -- Iron
Mn -- Manganese
Cu -- Copper
Zn -- Zinc
B -- Boron
Fe/Mn -- Iron/Manganese
C. -- Conductivity